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Software-defined traffic light preemption for faster emergency medical service response in smart cities☆

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ABSTRACT

Proper management of rescue operations following an accident is one of the most fundamental challenges faced by today's smart cities. Taking advantage of vehicular communications, in this paper we propose novel mechanisms for the acceleration of the rescue operation resulting in a reduction in fatalities in accidents. We propose a Software-Defined Traffic Light Preemption (SD-TLP) mechanism that enables Emergency Medical Vehicles (EMVs) to travel along the rescue route with minimal interruptions. The SD-TLP makes preemption decisions based on global knowledge of the traffic conditions in the city. We also propose mechanisms for the selection of the nearest emergency center and fast discharge of the route of EMVs. Furthermore, depending on the dynamic traffic conditions on the streets at the time of the accident, an appropriate rescue route is selected for the EMV before its departure. The proposed approach is evaluated using the OMNET++ and SUMO tools over part of the Megacity of Tabriz, Iran. The simulation results demonstrate that the method can reduce the average rescue time significantly. The proposed approach keeps the resulting disruption in city traffic acceptably low while trying to shorten the rescue time as much as possible.

1. Introduction

Recently, the concept of a "smart city" has gained a lot of attention. In modern smart cities, information and communication technologies are used more extensively than in the previous "less smart" cities. In particular, transportation systems constitute a significant part of modern life, especially in large smart cities. Given the unprecedented development of urban centers and the introduction of new services resulting from technological improvements, these systems increasingly need proper support for the management of resources and vehicles (Ipolito Meneguette, 2018; Chahal et al., Nov. 2017). One of the most important challenges in large cities is the minimization of mortality and financial loss due to accidents. According to the Global Road Safety Commission, accidents cause 1.3 million casualties and more than 50 million injuries every year. If quickly transferred to medical centers to undergo treatment, however, accident victims will quite likely recover. For this purpose, rescue vehicles need to be notified, arrive at the scenes, and transfer the injured to medical centers as quickly as possible (Nobre, Jan. 2019). Since rescue vehicles (such as fire trucks, ambulances, and police cars) have always been prioritized, when traveling along the routes and the intersections around the city, the strategies of *traffic light preemption* for Emergency Medical Vehicle (EMVs) are employed to ensure quick and nonstop travel (Shaaban et al., 2019). The ultimate goal of all traffic light preemption strategies is to reduce the rescue time to a value lower than a standard (desired) threshold. In this paper, the time it takes until the EMV arrives at the accident scene from the emergency station will be referred to as *rescue time* and the route selected for the EMV will be denoted as *rescue route*.

Intelligent Transportation Systems (ITS) play an important role in coordinating traffic and ensuring safety, which helps resolve lots of challenges in smart cities. Along with other technologies (such as machine vision, navigation, and radar technologies), the Internet of Things (IoT) and vehicular communications are key technologies that play an important role in modern ITS. These two major enabling technologies are nowadays known as the Internet of Vehicles (IoV). The improvements in the context of information and communications technologies have made it possible to design and implement solutions to develop ITS and provide modern services such as the promotion of safety,

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dissemination of useful information to drivers, and congestion avoidance (Ipolito Meneguette, 2018; Chahal et al., Nov. 2017). However, given today's large urban centers and the presence of a large number of vehicles, traffic lights, and roadside units (RSUs), the current architecture of communication technologies lacks flexibility and scalability in large-scale deployments. One of the most promising solutions to overcome this limitation relies on the concept of Software-Defined Everything (SDX), which is based on the separation of the data plane (executing agents) and control plane (decision-making agents). The main feature of SDX is centralized decision-making, which leads to better and more consistent decisions. Flexibility, planning capability, and centralized control can thus be added to the available infrastructures (Ku et al., 2014). Most of the proposed traffic light preemption strategies currently focus on local intersections. On the basis of local detection of EMVs in a road segment, the phase of the corresponding traffic light is controlled; this process often leads to unavoidable delays at the intersections. An alternative approach is used when the preemption system is applied to the entire route, from the initial location of the EMV to the accident scene. By interrupting regular traffic at intersections, the system provides a special Green route for EMVs to let them travel through intersections with fewer stops. In this case, even though the rescue time is reduced, the regular urban traffic is affected negatively. Therefore, a tradeoff solution is needed to achieve the desired value of rescue time while keeping the negative effect on regular traffic as limited as possible (Shaaban et al., 2019).

In this paper, our objective is to minimize the arrival time of the EMVs to an accident scene. For this purpose, in the first place, considering the current traffic conditions in the city at the time of the accident, an appropriate *rescue route* is specified for the EMV (before its departure). Then, during the travel toward the accident location, for further reduction of the rescue time, two mechanisms are applied: (1) a lane-changing mechanism, which is applied to vehicles ahead aiming at discharging the EMV route, and (2) a Software-Defined Traffic Light Preemption (SD-TLP) mechanism for enabling (ideally) nonstop EMV travel through intersections. In SD-TLP, a centralized controller is employed for the provision of a comprehensive view of and consistent access to all the traffic lights along the rescue route. This global view of routes and traffic lights leads to a shorter rescue time for EMVs and, at the same time, decreases the delay imposed on regular city traffic. In other words, we aim at an approach that minimizes the desired rescue time, while the regular city traffic is disturbed as little as possible.

The remainder of the paper is organized as follows. Section 2 provides a review of the previous works. The proposed techniques and algorithms are described in Section 3. Section 4 focuses on performance evaluation. Discussions, conclusions, and suggestions for future works are made in Section 5.

2. Previous works

Vehicular communications are considered one of the promising enabling technologies (along with other complementary technologies) for substantiating smarter ITS in smart cities. However, many challenges have to be faced. In (Ameen et al., 2020), the authors investigate the main components of an ITS system and review the main advantages of Vehicle-To-Vehicle (V2V) communications in this area, describing the applications enabled by such communications, including driver assistance; direction and route optimization; road safety; and traffic management. For instance, an alert mechanism for vehicular networks referred to as DRIFT is introduced in (de Souza et al., 2014), which not only notifies accidents on highways, but also uses route-switching mechanisms for other drivers to prevent greater congestion at accident scenes and reduce travel time, fuel consumption, and pollution. However, the area of emergency management is a relatively new field. In the following, we review the literature on the role of vehicular communications in emergency management, in the following three categories.

2.1. Application of SDX to vehicular networks

In (Ku et al., 2014), the authors investigate the effect of Software-Defined Networking (SDN) on the flexibility of route planning in vehicular networks, by connecting a central controller to the vehicle through cellular communication. The simulation results demonstrate that the routing efficiency is higher with SDN than without. Moreover, a mechanism of failure recovery is introduced that maintains the packet delivery rate at an acceptable level in case of disconnection from the central controller. Another technique for emergency message transfer using SDN is proposed in (Zhu et al., 2018). On the basis of the global view provided to the SDN controller, the most appropriate RSU and route are selected for message transfer, and V2V message dissemination is carried out in regions not covered by any RSU. Furthermore, the work of (Nobre, Jan. 2019) investigates the effect of the addition of fog computing to the vehicular SDN architecture. The new architecture is analyzed from three perspectives: network, system, and service. The simulation results demonstrate that the integration of fog computing and SDN may significantly reduce rescue time, particularly if a considerable number of vehicles available in the area accept the policies concerning emergency conditions.

2.2. Use of traffic light control techniques for traffic control

The authors of (Litescu et al., 2016) provide an illustrative investigation of the effect of vehicle interaction with traffic lights. In the presence of such an interaction, a vehicle can receive traffic light information and continue to travel on that basis so that it avoids congestion at the traffic lights.

Considering factors such as vehicle entry rate and maximum rate of vehicles' travel through an intersection, in (Schutter and Bart, and Bart De Moor., 1998) plans for traffic light switching are proposed, seeking to minimize average queue length and average waiting time. In (Krajzewicz, 2005), the congestion at each lane leading to an intersection is measured: a longer Green light will be set if the measured traffic density exceeds a threshold. The work of (Turky et al., 2009) uses genetic algorithms to control smart traffic lights, which is applied to an intersection involving four two-way input roads with two sets of parameters; (i) queues of vehicles and pedestrians at the Red light and (ii) the numbers of vehicles and pedestrians traveling through the Green light. In (García-Nieto et al., 2012), the authors suggest a particle swarm optimization algorithm, which seeks to control traffic lights over an area wider than the urban space. It begins with an initial population, involving particles' locations and speeds. Based on the simulation results, the use of the proposed algorithm increases the number of vehicles arriving at their destinations and their average travel times. Moreover, in (Bani Younes and Boukerche, 2014) the authors propose to reduce waiting time on all the streets leading to an intersection and to increase productivity. The presented algorithm guarantees that traffic is shared fairly at each intersection by the different flows.

2.3. Traffic light control for prioritization of EMV

In (Kamble and Kounte, 2022), a number of existing methods for emergency vehicle preemption are reviewed in detail. The models are categorized into three distinct groups, namely: "routing-based," "scheduling-based," and "miscellaneous". In (Hashim, Jul. 2013), a radio modem is used by emergency vehicles to notify their presence. Upon reception of an emergency alert at an intersection, the traffic light corresponding to the lane of the sender remains Green for a longer time and gets back to the normal state after the emergency vehicle crosses the intersection. In (Annan et al., 2021), a cost-effective system is designed and incorporated to detect the presence of an emergency vehicle at an intersection. Upon detection, the traffic light switches from its normal operation mode to the emergency mode and, then, resumes normal operation after the emergency vehicle passes the intersection. A dynamic system for switching traffic lights is presented in (Sangeetha et al., 2021), in combination with an emergency vehicle detection system to aid with the preemption performance and flow of traffic. The system uses a microcontroller equipped with an infrared sensor, as well as a microphone (to sense the strength of the horn of the ambulance present in the traffic jam) to monitor traffic and identify emergency vehicles. The work of (Salih et al., 2019) aims to present a dynamic preemption algorithm that seeks to establish a trade-off between two objectives: minimizing emergency vehicles (e.g., EMV) travel time and minimizing delay for other traffic. The authors of (Shaaban et al., 2019) present a method that enables control of one route with several intersections for an emergency vehicle to travel through. Besides the control mechanism, an appropriate route is specified in the paper for the emergency vehicle before its departure based on the traffic parameters. The work of (Humagain et al., Jan. 2020) is aimed at making a systematic investigation and comparison of optimization methods for route specification and preemption for emergency vehicles with a focus on factors such as the use of dynamic traffic data and minimization of the impact of preemption on other traffic. The authors of (Mu et al., Jan. 2020) focus on the transfer from the emergency vehicle signal preemption state back to the normal state after the emergency vehicle passes through the intersection. Given objectives such as increasing efficiency, providing fairness, and increasing the number of vehicles passing through the intersection at each cycle, a multi-objective transition optimization model is designed. The purpose of (Younes and Boukerche, 2018) is to present a dynamic scheduling algorithm for traffic lights that considers one or more emergency vehicles. The scheduling is based on a calculation of the longest Green time for a traffic light. Recently, the authors of (Zhong and Chen, 2022) proposed a novel real-time traffic signal control strategy, that is a “Green wave’’ signal control strategy, for emergency vehicles, ensuring the rapid driving of emergency vehicles by reducing road saturation in advance, providing emergency vehicles with signal preemption, and restoring the road network. The simulation was conducted utilizing the urban traffic simulator SUMO. In (Rego et al., Nov. 2018), integration of IoT and SDN is used to reduce the time it takes until an Emergency Vehicle arrives at the emergency area. In their proposal, the information about the emergency conditions arrives at a central controller. If a high-risk accident is identified, the scene will be marked, and a required traffic light preemption is performed. Furthermore, if possible, alternate routes are suggested to other vehicles to further smooth the travel of emergency vehicles. The purpose of (Bideh et al., 2019) is to present an SDN-based emergency traffic management application that provides the emergency vehicle with a quick, efficient route, presents a purposeful information system for the reduction of congestion on the rescue route, and seeks to reduce rescue time by controlling the traffic lights along the route, with little effect on the surrounding traffic. In (Bagheri et al., 2020), a novel mechanism utilizing SDN is introduced which provides an acceptable rescue time. However, the impact of the proposed mechanism on the regular traffic of the city is not investigated. The reference of (Rosayyan et al., 2023 Apr) proposes an optimal control strategy for emergency/preventive vehicle priority (EVP) using edge computing and IoT sensors for smart cities. This research was conducted using a GPS-based IoT sensor that continues to send location information (LI) to an edge server. The edge server calculates the optimal timing based on the proposed control strategy algorithm and clears the emergency vehicles.

The most related works to ours are (Zhong and Chen, 2022; Rego et al., Nov. 2018; Bideh et al., 2019; Rosayyan et al., 2023 Apr). The authors of (Zhong and Chen, 2022; Rosayyan et al., 2023 Apr) have introduced some strategies for managing emergency conditions and have achieved significant time savings. The distinctions of our method from these methods is the use of Software-defined controlling and its exceptional features in network management so that any changes in any part of the network can be easily handled and modified at the central management center. Besides, in (Rego et al., Nov. 2018), the use of SDN for traffic light preemption has been suggested by the authors. The implementation of this method assumes the existence of an alternative route (e.g., a ring road). Considering that it is not possible to replace the ring road for vehicles in all parts of the city, we suggest a lane-changing mechanism to clear the path and create smoother traffic. (Bideh et al., 2019) proposes the idea of software-defined controlling under the framework of software-defined networking (SDN), which we believe has many limitations when applied to large-scale and real-life scenarios. They use the concept of SDN and the relevant tools, such as RYU controller, Open Flow protocol, and Mininet emulation, for every vehicle and traffic light. This results in a huge computation overhead, and thus their scenarios only cover a small number of vehicles, such as 100 vehicles. Their evaluation does not consider the congestion level of the city traffic. In contrast, our work uses the concept of SDX, which is easy to implement, and our initial scenario starts from 1000 vehicles (more vehicles for more congested cases). Therefore, we can study the effect of traffic congestion levels on the performance of medical emergency response. Moreover, unlike (Bideh et al., 2019), our work also uses V2V communications for lane changing.

This study covers all stages of medical emergency control scenarios including accident notification, selection of the nearest medical emergency center, determination of the closest route, lane changing, traffic light control, and traffic light recovery. However, previous works, only cover some of the stages and/or use local decision-making. We have used a software-defined controller that takes advantage of centralized decision-making, which overcomes the issues present in local methods. The advantages of using software-defined controllers include increased network flexibility, cost reduction, improved efficiency, and reduced time for network changes. Another important aspect of our approach is its capability to avoid sudden and disruptive changes to normal city traffic while providing a satisfactory rescue route. Our work also includes a lane-changing mechanism for further reduction of the traffic in the accident area. Furthermore, we propose a post-preemption strategy (for bringing the traffic lights back to the normal state) using a global view of the urban traffic and intersections aiming at keeping the disturbance effect of traffic light preemption strategies as low as possible.

3. Proposed approach

Medical emergencies can be life-threatening and require immediate attention. In such situations, every second counts, and prompt medical intervention can make all the difference between life and death. Medical service and emergency vehicle preemption are crucial in such scenarios as they ensure that EMVs and other emergency vehicles can navigate through traffic and reach their destination as quickly as possible. This not only saves precious time but also ensures that the injured receive the necessary medical attention they require. Therefore, medical service and emergency vehicle preemption are essential components of a comprehensive emergency response system. Preemption operations are one of the most important factors in improving EMV response times to incidents. These operations allow EMVs to have priority in traffic and navigation systems to quickly reach the scene of the incident. This operation reduces response time and increases the likelihood of saving the lives of the injured.

Our proposed approach makes use of the idea of software-defined control to reach the flexibility required for the dynamic situation of city traffic. It uses centralized decision-making aiming at achieving the required flexibility of management. The advantages of using SDN

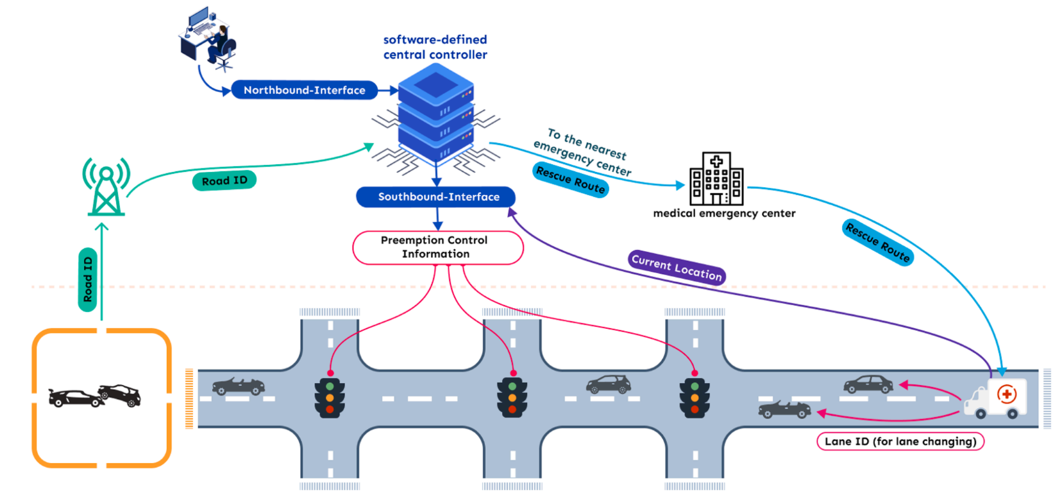

Fig. 1. Overview of the Proposed Appraoch

include increased network flexibility, cost reduction, improved efficiency, and reduced time for network changes. Fig. 1 shows an overview of the proposed approach.

In our system model, we assume that there are some RSUs deployed all over the city. The RSUs are capable of sending/receiving messages to/from vehicles. These RSUs can be IEEE 802.11p-enabled devices and/or LTE/5G base stations (Rammohan, 2023). In addition to DSRC which is inherently used for short-range communications and has lower latency, the capabilities of LTE and 5G can also be utilized. This is known as Cellular Vehicle-to-Everything (C-V2X) in 3GPP documents. Due to its utilization of existing cellular network infrastructure, this technology has a wider coverage and holds a better future compared to DSRC in particular for Vehicle to Infrastructure (V2I) mode. However, still, in Vehcile-to-Vehcile (V2V) mode, DSRC is superior in terms of latency.

In this study, the prerequisite is having a Traffic Information System (TIS) by which a central controller can have up-to-date information about the city traffic, etc. For this purpose, we have used vehicular networks with all their features, including vehicle-to-vehicle (V2V) communications and vehicle-to-infrastructure (V2I) communications. The basic assumption is that vehicles provide information such as ID, location, and speed during the transmission of beacons to RSUs (Roadside Units). Information such as accident locations, the number of vehicles in each road segment, average vehicle speeds, etc., are then extracted by the central controller. Once an accident occurs, the involved vehicles send out their road segment identification to the closest RSU via Vehicle-To-Infrastructure (V2I) communication. We assume that this message arrives at a centralized SD traffic light controller by inter-RSU networking. The technology connecting RSUs is beyond the scope of this paper, but there are some candidate wired and wireless technologies (including Commercial Off-The-Shelf (COTS) solutions). Upon reception of information from the accident scene, the controller enables the proposed search mechanism for the closest emergency center. The system manager sends control instructions to the software-defined central controller via the northbound interface. The controller performs calculations and determines the best rescue route, which it sends to the medical emergency center. The controller also communicates the results of the calculations and instructions to other components, such as traffic lights and EMV, via the southbound interface. The search and routing mechanism adopted in this step is based on Dijkstra's algorithm (Dijstra, 2020). We define the cost of each route based on its traffic density.

After receiving the accident scene identification, the emergency center dispatches an EMV through the controller-specified route. Along the specified rescue route, the EMV seeks to further reduce rescue time using *lane-changing* and *SD-TLP* mechanisms. In this section, the overall overview of the proposed approach is presented, involving the following two mechanisms.

1- Detection of the closest emergency center to the accident scene and identification of the best (tentative) route from the emergency center to the accident scene.
2- Further reduction of the rescue time during the travel via:
a- utilization of an SD-TLP mechanism along the route.
b- route discharge mechanism employing a lane-changing strategy for vehicles in front of the EMV;

Each of the proposed mechanisms is detailed below, along with a description of its method of employment.

3.1. Selection of the nearest emergency center and identification of the shortest rescue route

Identifying the nearest emergency center to the accident scene is the first efficient step, followed by determining the best rescue route. It should be noted that it is of great significance to use an appropriate measure of proximity (i.e., road segment cost), given the dynamicity of traffic conditions and its effect on road travel time. In the first component of our proposed approach, the controller searches for the closest emergency center and specifies the corresponding rescue route.

Algorithm 1 (detailed below), which is based on Dijkstra's algorithm, is used to find the shortest path from each emergency center (denoted by *ECi*) to the accident location (denoted by AP). Using a loop, the algorithm seeks, at each iteration, to determine the shortest path from the *i*th emergency center (*ECi*) to the *AP* (lines 3 to 9). Inside the loop, the original Dijkstra algorithm is used. The cost of each link (road segment) is calculated as L/S , where L indicates the length of the road segment (dimension: [m]), and S is the average road segment speed (dimension: [m/s]). The cost of a rescue route is the total cost of all the road segments that it includes. Then the closest Emergency Center (min EC) and the shortest path from that to the AP (i.e., minSP) are returned to the caller.

It should be noted that although Algorithm 1 chooses the appropriate route for the EMV as it departs from the Emergency Center to the accident location, the rescue route should be controlled adaptively. This is due to the dynamic nature of the traffic conditions and the potential for upcoming congestion at a specific part of the current rescue route. In the following, we propose two mechanisms aiming at this purpose.

Algorithm (1): Shortest Path Rescue Route

```
Inputs: EC, AP
Output: The rescue route, The closest Emergency Center
//Symbols: SPi: the shortest path from ECi to AP, EC: Emergency Centers' location set, AP:
  Accident Point's location,
    Function shortest path (EC):
        minSP=∅
        minEC = EC0
          For each ECi in EC:
              Run the Dijkstra algorithm starting from ECi to find the shortest path
  from ECi to AP (i.e. SPi)
          If (weight(minSP) > weight(SPi))
            minSP = SPi
            minEC = ECi
          end If
        end For
      Return minEC, minSP
end Function
```

Algorithm 1. Shortest Path Rescue Route Identification

3.2. Route discharge via lane-changing of vehicles ahead

Upon departure, the EMV can notify other vehicles of its presence utilizing V2V communications (e.g., using DSRC-enabled devices). Algorithm 2 (detailed below) relies on this mechanism. In lines 2 and 3 of Algorithm 2, the EMV sends the ID of the lane it is traveling to vehicles present on the rescue route. In lines 4 to 9, vehicles that receive the message will attempt to discharge it if they are in the same lane as the EMV.

Algorithm (2): Lane Changing Algorithm

```
//Symbols: EMV: Emergency Vehicle's ID, AP: Accident Point's location
// Each vehicle receiving the alarm message from the EMV changes the lane if it is the same
  as the lane of the EMV
1:  Function Lane Changing():
2:      While EMV did not reach AP:
3:          send(lane of EMV) // emergency vehicle keeps sending its lane number
4:          For all receivers:
5:            If (lane = lane of the EMV) //if the vehicle is in the emergency lane
6:              change lane();
7:            end If
8:          end For
9:      end While
10:   end Function
```

Algorithm 2. Lane Changing Algorithm

This algorithm tries to reduce the congestion of road segments in front of EMVs as much as possible. It reduces rescue time to some extent. However, in the case of severe congestion or the availability of only one lane for each vehicle to travel, it is impossible to change lanes and discharge the route for the EMV. In such conditions, a more efficient solution is required to face congestion, particularly at intersections. The next proposed mechanism addresses the intersection and tries to reduce the congestion at the intersections for the EMV.

3.3. Software-Defined traffic light preemption (SD-TLP) on the rescue route

A more efficient solution for the reduction of rescue time is to employ the technique of route preemption for the EMV, i.e., its provision with an exclusive route to travel nonstop. In our proposed approach, we utilize the idea of Software-Defined Everything (SDX), according to which the controlling agent of all traffic lights (including those available along the rescue route) is moved to a software-defined central controller. This controller can configure traffic lights by any southbound API interface. The comprehensive global view of the traffic lights and traffic in their surrounding helps us to plan a more efficient preemption strategy. Algorithm 3, lists the steps of the proposed approach. The parameters used in Algorithm 3 are summarized in Table 1.

Table 1
Main parameters used in Algorithm 3.

Parameter	Definition
ET	The appropriate time to start the preemption operation: This is the time needed to clear the queue of vehicles ahead of the EMV at the traffic light on the current road segment (seconds)
C	Number of vehicles present on the road segment
L	Average vehicle length (meters)
MG	Minimum Gap between vehicles (normal city traffic: 2.5 m, congested traffic: 1 m)
S	Current road segments' average speed (meters per second)
DD	Appropriate distance from the EMV to the traffic light for preemption to begin (meters)
EVS	Current EMV speed (meters per second)
r	A constant numerical value representing the delay in traffic light phase switching (3 s)

The proposed algorithm is composed of three parts. The *first part* involves a calculation of the appropriate time and location for the preemption operation to begin. For this purpose, the EMV needs to send its location information to the RSUs until it arrives at the accident scene, as indicated in lines 2 and 3. If its entry onto a new road segment is detected by the software-defined controller, the values of an estimated time for discharge of the current road segment and detection distance are calculated for the new road segment based on (2) and (3), as indicated in lines 5 and 6:

$$ET = \frac{C \bullet L + ((C-1) \bullet MG)}{S} + r \tag{2}$$

$$DD = ET \bullet EVS. \tag{3}$$

The goal of (2) is to determine the proper time to start the preemption operation: This is the time needed to clear the queue of vehicles ahead of the EMV at the traffic light on the current road segment. By knowing the value of ET, the traffic light does not have to turn green earlier (for example, when the EMV enters the road segment, which is a common practice in many previous strategies). This leads to a more efficient phase control. The appropriate time for the control process to begin is when the EMV arrives at an appropriate distance from the traffic light, calculated in turn from (3) using the time obtained from (2) and the EMV speed.

After DD is calculated, the control operation begins once the EMV is as close as DD to the traffic light, as indicated in lines 13 to 20 of Algorithm 3. That is, if the current phase is Red, it turns to Green (the duration of Red is reduced in line 15); if the current phase is Green, the phase duration is prolonged (line 18).

In the *second part* of the algorithm, involving lines 21 to 30, the algorithm continuously monitors the next two traffic lights along the rescue route, adjusting the traffic signal for any of them to green if the corresponding road segment exceeds a traffic load of 70 %. This action is taken to maintain a balanced and smooth flow along the rescue route before the Emergency Medical Vehicle (EMV) enters the road segment. This is done to prevent sudden traffic condition changes as much as possible.

The value of 70 % should be set according to the case under study (the traffic conditions and road segment lengths, etc.). In our simulation environment, we have done extensive tests to reach this threshold value. If this threshold value is set higher than an appropriate value, congestion might have exceeded its limit before the EMV enters the road segment. In this case, the road segment is not cleared before the EMV enters which makes the rescue route less fluent and increases rescue time. On the other hand, if the threshold value is set lower than an appropriate value, there might be no need to change the traffic light phase. Unnecessary manipulation of the traffic light would disrupt the normal traffic flow without any significant benefits.

The *third part* of the algorithm is a post-preemption approach. According to lines 7 to 11 of Algorithm 3, a preemption recovery is examined as follows. After the Emergency Medical Vehicle (EMV) passes the current intersection, the distance between the current traffic light and the previous one is considered. If this distance is above a threshold, only the current traffic light changes to Red. Otherwise, both traffic lights are turned to Red. This mitigates the normal traffic disruption caused by our preemption mechanism and in particular, improves the AWT metric compared to the Local Preemption mechanism.

Algorithm (3): Software-defined Traffic Light Preemption (SD-TLP)

```
Inputs: EMV's location, Traffic lights location in the rescue route, AP, C, L, MG, S, EMVS,
Action: The appropriate time and location for the preemption operation to begin, changing
   the traffic lights to Green
//Symbols: EMV: Emergency Vehicle's ID, AP: Accident Point's location, TL: traffic light's
   ID, Dtls: The distance between two consecutive traffic lights, Dtreshold: threshold distance
   between two consecutive traffic lights, DEMV: Distance of emergency vehicle to traffic
   light, TD: traffic density
Function SDX-based Preemption (AP):
    While EMV did not reach to AP:
      EMV send (road id)
      If it is a new road segment
            Compute ET using equation(2)
            Compute DD using equation(3)
          For previous traffic lights: //traffic lights recovery mechanism
            If (Dtls < Dtreshold)
              Set the second TL phase as the first TL phase
            end If
          end For
        end If
        else If (DEMV <= DD) // if the EMV is within the detection distance
            If (TL phase = "Red")
              reduce phase duration;
            end If
          If (TL phase = "Yellow")
              change phase to Green;
          end If
      end If
      For the next two lights:
      If (TD > threshold) // if traffic density is high
        If (TL phase = "Red")
              reduce phase duration;
            end If
          If (TL phase = "Yellow")
            change phase to Green;
          end If
        end If
      end For
    end While
  end Function
```

Algorithm 3. Software-defined Traffic Light Preemption (SD-TLP) Algorithm

4. Performance evaluation of the proposed approach

In this research, we use OMNET++[1] as a network simulator, SUMO[2] as a tool for the city traffic simulation, and VEINS[3] as a tool for the establishment of a link between the network simulator and the mobility simulator (OMNET++,2023; SUMO simulator,2023; VEINS, 2020).

The urban location selected for implementation of the proposed approach is a district in the Megacity of Tabriz, East Azerbaijan Province, Iran, a map of which has been extracted from the Open Street Map website (OSM, 2023). The extracted urban map is shown in Fig. 2 along with the locations of the emergency centers. The area is chosen based on the availability of emergency centers inside the city. For covering the entire city, we propose a hierarchical architecture based on which the entire city is divided into smaller areas and use a controller for each area. Then a higher-level controller (a Global Controller) should control the Area Controllers. Relevant information on the considered scenario and simulation parameters is summarized in Table 2.

In our simulation, we have relied only on vehicular Communication with a 100 % penetration rate. If some vehicles are not equipped with radio communication capabilities, then the information we have about the congestion level of the road segments becomes inaccurate which negatively impacts the performance of SD-TLP. For such low penetration scenarios, other technologies like machine vision techniques, etc. might be deployed.

4.1. Performance metrics

The purpose of this paper is to provide appropriate management of medical emergency scenarios after the occurrence of accidents. In this regard, the first step is to reduce the time required by an EMV to arrive at the accident scene from the emergency center, i.e., to reduce rescue time. The following three performance metrics are considered.

- **Average Rescue Time (ART)**

As previously defined, ART is the average time it takes an EMV to arrive at the accident scene from a selected emergency center.

- **Average Imposed Waiting Time (AIWT)**

Appropriate management is provided so that the mechanisms developed for decreasing the rescue time have the lowest possible impact on normal city traffic. In other words, the delay imposed at intersections along the rescue route on vehicles traveling routes intersecting that of the EMV should be kept reasonably low. Therefore, the second criterion is the *average waiting time imposed on vehicles traveling on the routes that intersect that of the EMV.*

- **Average Waiting Time on Rescue Route (AWT)**

Due to the phase switching made to the traffic lights available along the route, the coordination between traffic lights close to each other may be disturbed once the rescue operation is completed: This will have a negative impact on the vehicles traveling along the rescue route, thereby increasing their delay. Therefore, the proposed approach should prevent an unnecessary disorder by considering a recovery mechanism. Thus, the third criterion is the *average waiting time for the vehicles traveling on the same route as that of the EMV.*

4.2. Performance evaluation

For assessment, we implement and consider the following six scenarios.

- **Normal State**

The normal, i.e. default, traffic state with regular traffic light functionality and no additional implemented mechanism.

- **Lane-changing**

Implementation of the mechanism proposed for lane-changing of vehicles ahead of the EMV.

- **Full Preemption**

Implementation of a strategy where all the traffic lights along the route turn to Green upon the arrival of the EMV to the corresponding road segment. After the EMV passes the traffic light, it turns Red.

- **Local Preemption**

[1] Objective Modular NETwork Testbed (OMNET).
[2] Simulation of Urban MObility (SUMO).
[3] VEhicles In Network Simulation (VEINS).

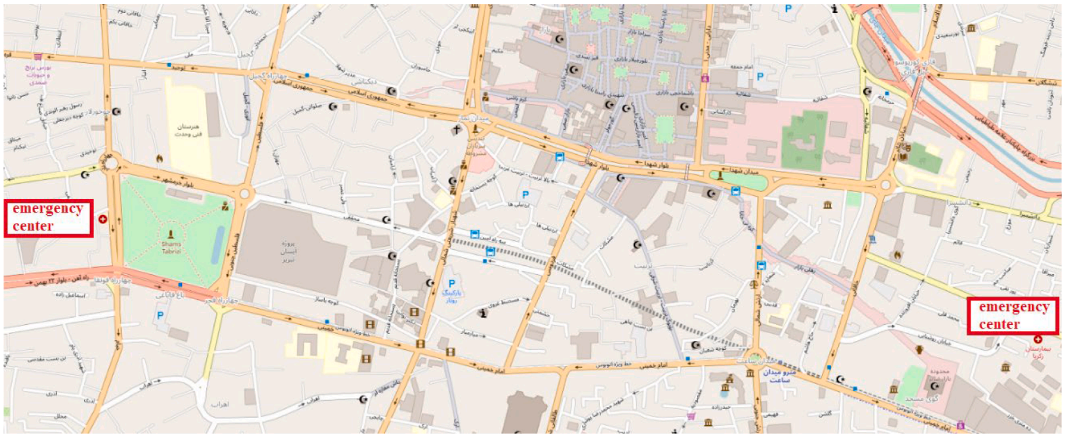

Fig. 2. The portion of the Tabriz Megacity map for which our approach is simulated.

Table 2
Main simulation parameters in the considered scenario.

Parameter	Value
OSM bound box	46.2760,38.0817,46.3045,38.0725
The map	Tabriz city
Vehicle Transmission Power (to send/receive messages)	30mW
RSU Transmission Power (to send/receive messages)	60mW
Number of emergency centers	2
Number of RSUs	8
Number of SDN controller	1
Simulation time	1800 s

Implementation of the strategy of controlling each traffic light locally and independent of others.

- **SDN-based Preemption**

Implementation of the proposed traffic light control mechanism (SD-TLP).

- **SDN-based Preemption + Lane-changing**

Implementation of the SD-TLP along with the mechanism proposed for the lane-changing mechanism.

The accident occurs 300 s after the beginning of the simulation, regarded as warm-up time, during which the number of vehicles traveling in the city reaches a relevant and steady value. To ensure that the method performs correctly, we replicate the simulation for ten random days. We measure the performance metrics outlined above (namely: ART, AIWT, AWT) for different levels of congestion. The AIWT and AWT criteria are calculated after the additional time duration, after the EMV arrives at the traffic location, to ensure the stability of the regular city traffic. In this way, we can have a more fair evaluation to assess the disturbance effect of the regular city traffic by our emergency management operation.

For simulating different levels of congestion, we have generated 5 traffic flows using SUMO (with different flow rates) in 6 random paths inside the city such that the rescue route is affected and gets congested. In the assessments, the horizontal axis represents the average number of vehicles traveling the route ahead of the EMV once it begins to travel until it arrives at the accident location. In each congestion level scenario, this number is calculated for each road segment upon the entry of EMV, and the final numbers are obtained by averaging over ten days. In other words, in the following figures, N_v is the average number of vehicles ahead of EMV in the rescue route.

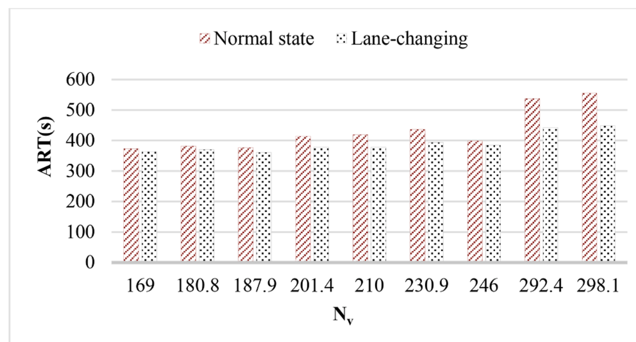

Fig. 3. ART of the lane-changing scenario, as compared to the ART of the normal scenario.

4.2.1. *Evaluation of the effect of the lane-changing mechanism*

Fig. 3 shows the ART obtained from the implementation of the lane-changing scenario, as compared to that in the Normal scenario.

On the basis of the obtained results, it can be concluded that the lane-changing mechanism can reduce rescue time to some extent, but the amount of improvement cannot exceed a certain level due to the presence of obstacles such as Red lights along the rescue route, single-lane routes, and the impossibility of lane-changing because of congestion.

Fig. 4 and Fig. 5 show the AIWT and AWT along the rescue route, respectively, for the lane-changing method. As it is clear from the obtained results, the lane-changing mechanism fails to considerably affect the waiting times of other vehicles, since it applies no control operation to the traffic lights along the route.

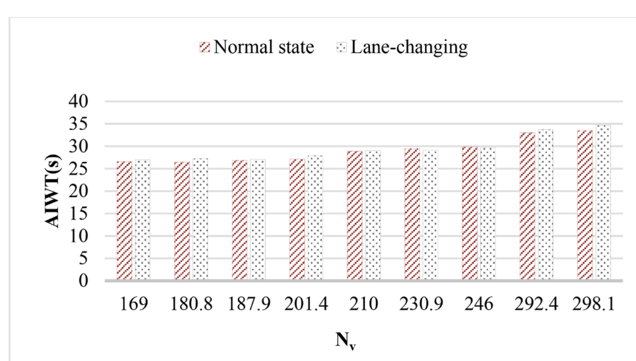

Fig. 4. AIWT of the lane-changing scenario, as compared to the AIWT of the normal scenario.

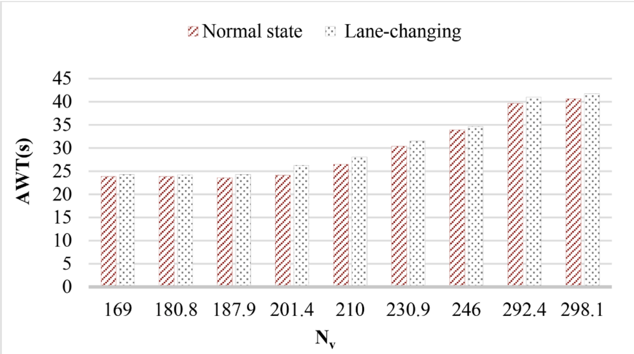

Fig. 5. AWT of the lane-changing scenario, as compared to the AWT of the normal scenario.

Therefore for a considerable reduction of the rescue time, traffic light control techniques must be used. It should be noted that the shortest rescue time will be achieved if all the traffic lights along the route are Green, and the EMV travels the route nonstop (the Full Preemption strategy).

4.2.2. Evaluation of the effect of the Full preemption mechanism

The Full Preemption scenario can be considered the ideal scenario for the EMV in terms of rescue time. However, it affects the normal traffic of the city quite negatively. As a result, it cannot be used in practice. Nonetheless, we can use it as a benchmark for assessing other mechanisms in our approach. In Fig. 6, we compare the ART in the Normal state (when no mechanism is in place) and with the Full Preemption (ideal condition; when all of the traffic lights along the path are Green).

The observed results show that the ART often increases as does the average number of vehicles present on the rescue route. It should be noted that an increase in the number of vehicles does not necessarily increase the rescue time in some cases, where factors such as direction, travel lane, and vehicle routes are effective. If the Full Preemption strategy is applied, however, the average rescue time will be reduced considerably for any traffic volume, since all the traffic lights present along the rescue route are turned green during the rescue operation.

Fig. 7 shows the AIWT criterion in both the Normal and the Full Preemption scenarios. From the results of Fig. 6 and Fig. 7, it can be concluded that the average delay imposed on intersecting vehicles at the intersections along the rescue route is not negligible in the Full Preemption scenario, although the best rescue time for the EMV is achieved. This is because all traffic lights along the rescue route are Green: this is unnecessary and imposes a significant delay on vehicles traveling along routes intersecting that of the EMV.

Therefore, the appropriate approach is the one that can maintain AIWT close to that of the Normal state and, at the same time, provide a low ART. In other words, rescue operation acceleration techniques

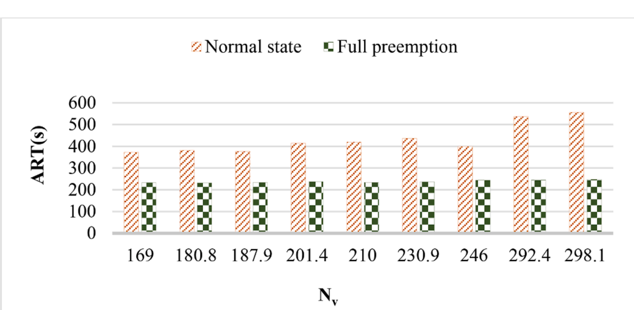

Fig. 6. ART of the full preemption scenario, as compared to the ART of the normal scenario.

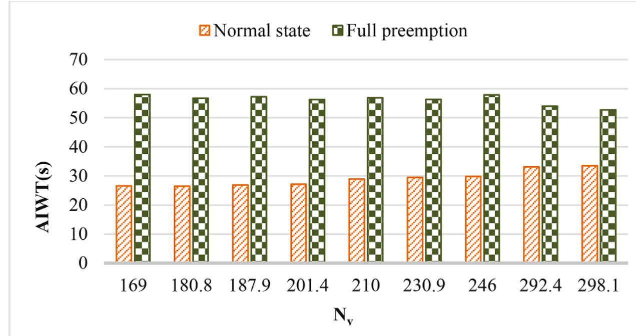

Fig. 7. AIWT of the full preemption scenario, as compared to the ATWT of the normal scenario.

should not influence public urban traffic to a great extent.

4.2.3. Evaluation of the effect of the Local preemption mechanism

As noted earlier, an available solution in the literature that is proposed for the reduction of rescue time and its impact on regular traffic is the Local traffic light preemption, where each traffic light is controlled independently of others. Fig. 8 illustrates the steps required for the local preemption mechanism implemented in this paper. In the following figures, we evaluate the performance obtained with this mechanism compared to the Normal and Full Preemption scenarios.

Fig. 9 shows that this method reduces rescue time to a desirable extent, particularly for light traffic conditions. The local preemption method leads to rescue times shorter than the normal conditions.

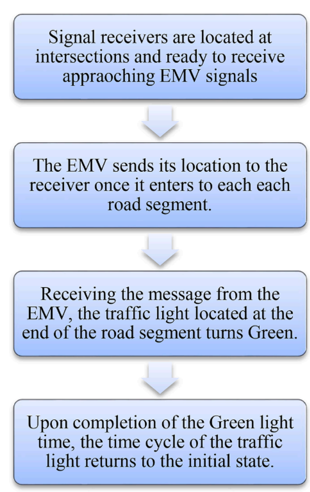

Fig. 8. Local control mechanism of traffic lights on the rescue route.

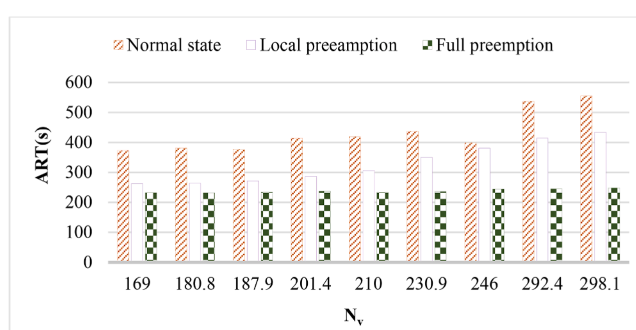

Fig. 9. The ART of the Local Preemption scenario compared to that of the other strategies.

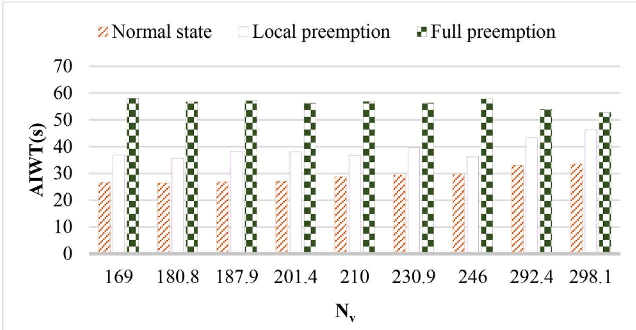

Fig. 10. The AIWT of the local preemption scenario, as compared to the AIWT of the previous scenarios.

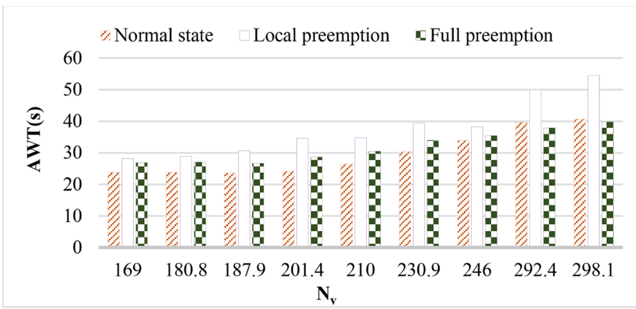

Fig. 11. The AWT of the local preemption scenario compared to that of the previous scenarios.

However, the rescue time growth rate in the Normal state and the local preemption are fairly similar. As traffic becomes heavier, the improvement effect of this policy is also limited. This can be explained by the following reasons.

1- There might be so much congestion at the road segments of a traffic light that the EMV fails to arrive within an appropriate distance from the traffic light to begin the preemption operation. Note that, in the Local Preemption scenario, there is no central controller and the EMV has to communicate with each traffic light directly.
2- At the Local Preemption, the EMV considers only the first immediate traffic light in its path and has no information about the next lights and the distance between them. In some cases, the traffic lights may be so close together that the behavior of a traffic light affects the other. This causes inconsistencies in the traffic lights and disrupts traffic along the rescue route.

The above issues are the drawbacks of the Local Preemption method. The SD-TLP will handle these limitations of the Local Preemption method using the general view of the central controller.

Fig. 10 shows the AIWT, as a function of the average number of vehicles in the rescue route, in the following scenarios: the Local Preemption; The Normal state; and the Full Preemption. The obtained results show that AIWT with the Local preemption is higher than that with the Full Preemption.

Moreover, Fig. 11 shows the AWT for the Local preemption scenario. As can be observed from the results in Fig. 11, AWT increases as traffic congestion increases. In lighter traffic loads, the EMV can travel nonstop across the intersections; therefore, independent traffic light control performs acceptably. However, as traffic becomes heavier, it is more likely that the EMV travels through intersections with a longer delay (due to the above-mentioned reasons. This increases the AWT along the rescue route.

As a summary, the advantages and disadvantages of the implemented scenarios are summarized in Table 3. The proposed lane-changing method, as can be inferred from Table 3, is insufficient on its own; it is essentially a supplementary mechanism to SD-TLP for specific traffic conditions. This mechanism is effective when the traffic is light, and vehicles have the opportunity to change lanes. If heavy traffic, congestion could build up behind red traffic lights at intersections or elsewhere, preventing vehicles from changing lanes. Therefore, this mechanism alone would not significantly reduce the Average Response Time (ART) for the entire route. A desirable approach should guarantee the desired ART and keep AWT and AIWT as low as possible.

In the subsequent sections, we will demonstrate the effectiveness of SD-TLP as a successful strategy and evaluate its ability to overcome the limitations observed in the strategies mentioned in Table 3.

4.2.4. *Evaluation of the effect of the SD-TLP mechanism*

The proposed SD-TLP mechanism aims at improving the drawbacks mentioned in Table 3. Fig. 12 shows the ART for the proposed approach as compared to the previous strategies. As shown in the figure, the SD-TLP mechanism leads to a better ART compared to other approaches. Indeed, SD-TLP can set the appropriate time and location to start traffic light control operations given the congestion level of the current road segment. The location of the EMV is continuously under control and there is no need for the EMV to be at a particular distance from the traffic light for triggering the preemption process. Furthermore, the rescue route is continuously monitored to control congestion not only at the current intersection but also at the subsequent intersection, thereby preventing the EMV from encountering severe congestion at the next intersection. This helps in keeping traffic light and guarantees near-optimal rescue time for any traffic volume.

Fig. 13 shows the AIWT for the proposed method as compared to the previous ones. Based on the obtained results, the proposed method can maintain AIWT at an acceptable level for the vehicles traveling on the routes that intersect the EMV route. SD-TLP performs better in terms of AIWT than Local Preemption, as the control operation begins at the appropriate time thanks to the global view provided by the centralized software-defined controller.

Finally, Fig. 14 shows the AWT for the proposed method as compared to the previous methods. Based on the obtained results, in very light traffic, the local preemption approach performs slightly better than SD-TLP. This is due to the fact that, with the Local Preemption, the traffic light phase is switched to Green immediately upon entry onto each road segment (earlier than SD-TLP), and more vehicles on the same route of the EMV can pass through the intersection. In moderate and heavy

Table 3
Advantages and disadvantages of the implemented scenarios.

Strategies	Advantage	Disadvantage
Lane-changing	reduction of ART as compared to the Normal state scenario and induction of no disorder in current traffic in the city	Limited reduction of ART and failure to ensure the reduction in different traffic conditions
Full Preemption	Provisioning of the lowest ART	Unacceptable increase in AIWT
Local Preemption	Provisioning of balance in AIWT and proper ART and AWT in light traffic	Poor performance in the reduction of ART in heavy traffic, along with interruption of coordination among traffic lights close to each other and consequent increase of AWT

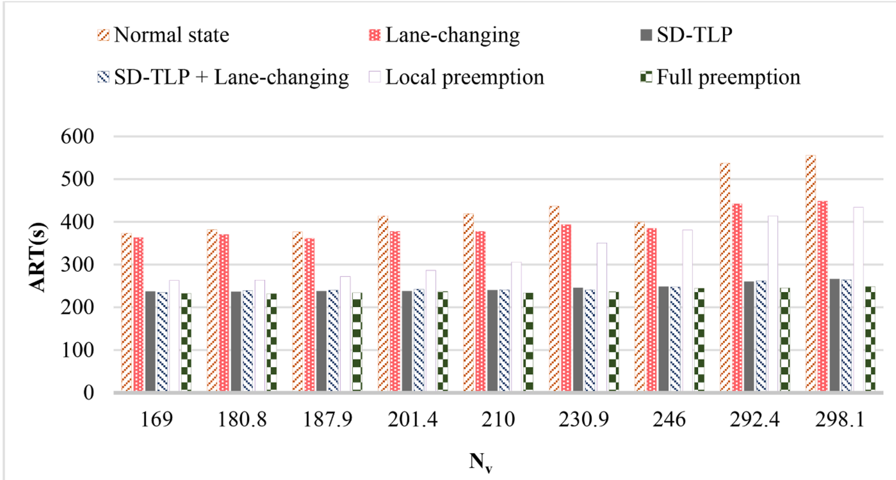

Fig. 12. The ART of the SD-TLP compared to that of the previous scenarios.

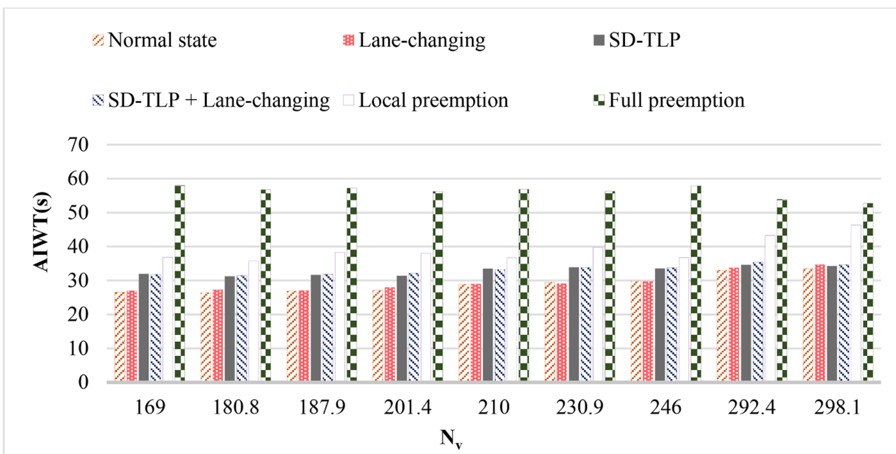

Fig. 13. The AIWT of the SD-TLP compared to that of the previous scenarios.

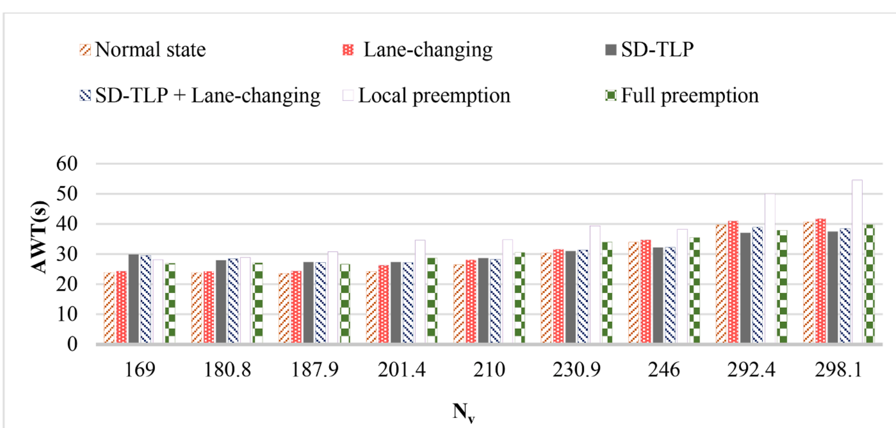

Fig. 14. The AWT of SD-TLP compared to that of the previous scenarios.

traffic conditions, SD-TLP performs much better than the other control methods and can better manage the disorder caused by traffic lights, thanks to the post-preemption mechanism (refer to Algorithm 3) which recovers the state of traffic lights after the EMV passes the traffic light.

Regarding Figs. 12, 13, and 14, as discussed in Section 4–2-1, the lane-changing mechanism alone has no significant impact on the AWT and AIWT metrics. Therefore, there is not a substantial difference between the results of SD-TLP and SD-TLP + Lane-changing for these two metrics. In the case of the ART metric, the lane-changing mechanism is a supplementary mechanism to SD-TLP and is effective only for light traffic conditions. On the other hand, because the SD-TLP mechanism provides results very close to the optimal solution (i.e., The Full Preemption), the presence of another supplementary mechanism alongside SD-TLP does not create a noticeable change in the ART value, particularly for heavier traffic conditions.

5. Conclusions and future works

In this paper, taking advantage of the global view and knowledge of the city traffic that is provided by a centralized controller, we proposed a traffic light preemption mechanism for faster medical emergency response. Our proposed mechanism covers all the stages of the medical emergency control scenario including accident message transmission, selection of the nearest emergency center, choosing the closest route, lane changing, traffic light control, and traffic light recovery. In this research, we aim to not only provide effective strategies for controlling medical emergency scenarios but also to enable the management of this control with minimal time and cost. Therefore, we believe that using software-defined control in this research is advantageous, not only because of its global view of the city traffic and more efficient decisions but also because of its ease and flexibility in applying appropriate control tasks.

Results show that the proposed approach namely SD-TLP keeps the resulting disruption in city traffic acceptably low (as demonstrated in Figs. 13 and 14) while trying to offer a rescue time noticeably close to the optimal strategy i.e., the Full Preemption, as demonstrated in Fig. 12.

Some possible directions for future works are: 1) applying the proposed method to scenarios with larger numbers and different types of EMVs, such as fire engines and police cars, and assigning different priorities to them; 2) the adoption of alternative technologies, such as C-V2X, to enhance communication between the controller, network infrastructures, and vehicles.; 3) formulating the preemption scheduling problem as an optimization problem that uses traffic information and seeks optimal solutions.

Author contributions

Nazila Bagheri has conducted the main literature review and simulation activities and has written the initial manuscript draft and the response letter for the revised version. Saleh Yousefi defined the research topic and supervised the research process along with revising/restructuring the initial draft and the revised version. He has designed the evaluation scenarios along with assessment methods. Gianluigi Ferrari has advised on the topic selection and also during the research process. He also significantly helped in the prepration of the initial draft and the revised version. He has also helped in designing the evaluation scenarios along with assessment methods.

CRediT authorship contribution statement

Nazila Bagheri: Conceptualization, Software, Writing – original draft, Writing – review & editing. **Saleh Yousefi:** Conceptualization, Methodology, Validation, Writing - original draft, Writing - review & editing, Supervision, Project administration. **Gianluigi Ferrari:** Conceptualization, Methodology, Writing - original draft, Writing - review & editing, Supervision.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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