



Autonomous Distributed Intersection Management for Emergency Vehicles at Intersections

Cesar L. González^{1,3}, Juan J. Pulido², Juan M. Alberola^{1(✉)}, Vicente Julian¹,
and Luis F. Niño²

¹ Institut Valencià d'Investigació en Intel·ligència Artificial (VRAIN),
Universitat Politècnica de València, Valencia, Spain

{cegonpin,jalberola,vinglada}@dsic.upv.es

² Universidad Nacional de Colombia, Bogotá, Colombia

{jjpulidos,lfnino}@unal.edu.co

³ Universidad ECCI, Bogotá, Colombia

Abstract. In recent years, numerous approaches have attempted to develop traffic control strategies at intersections. The complexity of a dynamic environment with different vehicles crossing in different directions and in some cases, with multiple conflict points, is a major challenge for the traffic optimisation, especially in urban areas. Work has focused on developing systems that range from intelligent traffic lights to complex centralised protocols that evaluate the policies to be met by vehicles at the intersections. In general, a traffic control system at intersections gives the green light to one lane, while keeping all other lanes on red light. But, what happens when there are several levels of vehicle priority or when there are emergency vehicles in the lanes? This feature needs a special protocol because of the high risk of collisions with other vehicles and the possible improvement in waiting times for emergency vehicles. Therefore, this paper proposes an emergency vehicle attention protocol with an algorithm that implements rules based on the protocol called Distributed Intersection Management (DIM) that is used by autonomous vehicles while negotiating their cross through the intersection. This proposal also seeks to avoid affecting the traffic flow of normal vehicles while the algorithm gives priority to emergency vehicles.

Keywords: Autonomous distributed intersection management ·
Emergency vehicle · Vehicle coordination

1 Introduction

Nowadays, the challenges of research in transportation systems have been complemented with the use of technologies capable of assuming the complexity associated with the possibility of communication and interaction between vehicles and with the infrastructure. These technologies must take into account that vehicles always meet the conditions necessary to maintain safety on the road. When

a vehicle does not meet these safety conditions, the control of the implemented technology has to intervene to avoid a possible collision of the vehicle, especially, at an intersection. Although there are still numerous problems to be solved in this type of system, the use of intelligent algorithms explores new and better ways to solve these problems.

Apart from safety, other important objectives of transportation systems research are the optimisation of flow, reduction of pollution or travel time used by vehicles in their movements. All this must be taken into account in order to validate in which type of road infrastructures it is necessary to make greater contributions.

Communication between vehicles facilitates their coordination in order to achieve the aforementioned objectives. In recent years, many studies have focused on providing a certain degree of coordination between autonomous vehicles, mainly at the moment of crossing, since this is one of the most critical situations that require the collaboration of vehicles circulating on different roads. Some examples can be found at [1–6].

Most of the proposals focus on offering centralised solutions by means of some type of infrastructure, although there are also decentralised solutions where vehicles arriving at an intersection form a network that collaboratively decide on the actions to be taken to speed up the flow through the intersection. An example of this type of proposal is presented in [7], where a series of crossing rules are proposed for the coordination management of autonomous vehicles. Thus, a collaborative behaviour emerges if the vehicles follow the rules.

A key element in this type of conflict situations at vehicle intersections is the management of vehicles with possible priorities such as emergency vehicles. In this particular case, we can also find previous works that try to speed up the flow of emergency vehicles in intersections versus non-priority vehicles.

In [8], the authors showed how it is possible to integrate the specific features of attention of emergency vehicles in a vehicular flow simulator. Moreover, in [9] authors implement a strategy about attention emergency vehicles where the policy gives more priority at the lanes where there is emergency vehicles, consequently, the delays on emergency vehicles will be less than normal vehicles. The approach that can be found in [10] tries to avoid delays in the emergency vehicles giving the priority of crossing in the lane where there is emergency vehicle without affecting with long delays other lanes with other vehicles. In a similar way, in [11] they present a centralised proposal taking into account the distance of the emergency vehicle to the intersection and the arrival probability to the intersection. The centralised control changes the traffic lights, including the traffic light for pedestrians.

In a different way, semi-centralised approaches can be found, for instance, the work in [12] includes some low cost infrastructure in the lanes improving the traffic light system. There exists communication between the different control systems of the proposed infrastructure adjusting the traffic light when there are emergency vehicles. Self-organised approaches are also proposed, for instance, in [13] authors use a protocol called VTL-PIC, where they change the normal

traffic lights in the intersections into a virtual traffic light. The protocol establishes that when several vehicles arrive at the intersection and if they detect a possible conflict, then a leader is elected who will manage the traffic in the intersection. Finally, [14] presents an IoT-based approach for emergency vehicle priority and self-organised traffic control at intersections. An intersection controller gets emergency vehicle positions (through GPS devices installed in the emergency vehicles) and vehicle density data at each lane approaching an intersection. The controller can adjust the traffic lights according to detected traffic.

As can be seen, numerous works have been carried out to optimise the flow of emergency vehicles at intersections. Most of these works focus on proposing centralised solutions. In an alternative way, this paper presents an extension of the work presented in [7] where a distributed coordination management system for intersections of autonomous vehicles was proposed. This extension focuses on prioritising the crossing of emergency vehicles, while minimising the impact on the flow of normal vehicles. Some experimentation was carried out on the SUMO¹ simulator to demonstrate the feasibility of the proposal.

The rest of this paper is structured as follows. In Sect. 2, we describe the Distributed Intersection Management model for Emergency vehicles. In Sect. 3, we show several experiments in order to validate the proposal. Finally, in Sect. 4, we draw some concluding remarks and suggest some future research lines.

2 Emergency Vehicles Model

In this section, we present the coordination model for emergency vehicles. This model is based on the Distributed Intersection Management (DIM) model [15], which provides autonomous vehicles with the capacity to negotiate and manage crossings at intersections. The DIM model is composed by three parts: the traffic flow model, the autonomous vehicle model, and behavioral roles. The traffic flow model is based on the LAI [16] model for large traffic networks simulation. Basically, this model represents the mechanism to maintain safe distances among the vehicles, guaranteeing safe driving, by defining the following rules:

- A vehicle a_i can accelerate as long as exists a distance D_{acc} between this vehicle and the vehicle that comes before a_{i+1} .
- A vehicle a_i keeps its velocity as long as exists a distance $D_{keep} < D_{acc}$ between this vehicle and the vehicle that comes before a_{i+1} .
- A vehicle a_i has to decrease its velocity if exists a distance $D_{brake} < D_{keep}$ between this vehicle and the vehicle that comes before a_{i+1} .

Autonomous vehicles can be represented as a group of agents $A = a_0, \dots, a_n$. Each vehicle a_i includes sensors to detect other vehicles that are inside an area. Each vehicle is also provided with a wireless communication system to send messages and request information to other vehicles. Taking into account this

¹ <https://www.eclipse.org/sumo/>.

model, autonomous vehicles are able to negotiate their own crossing without help of devices like traffic lights, sensors or traffic infrastructure.

Finally, an autonomous vehicle can play two different roles: follower (F) and negotiator (N). These roles depend on the information and the specific actions that a vehicle can carry out. The follower role is played by autonomous vehicles that are moving just behind another vehicle. In contrast, the negotiator role is played by autonomous vehicles that do not detect other vehicles inside their communication areas and before the next intersection. In Algorithm 1 we can observe the coordination algorithm for intersection crossing. This algorithm determines which autonomous vehicle should cross an intersection when a conflict with other vehicles occurs.

Algorithm 1. Coordination intersection crossing

Require: An autonomous vehicle a_i with role N .

Ensure: Cross the intersection; otherwise stop.

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1: while  $a_i$  arrives at intersection  $k$  do
2:   Broadcast its distance and velocity over  $k$ 
3:   if There is not a response by any vehicle then
4:      $a_i$  can cross with priority the intersection  $k$ 
5:   else
6:      $a_i$  should evaluate crossing for avoiding collisions and block the intersection  $k$ 
7:     if There is a fleet of autonomous vehicles crossing the intersection  $k$  in a
       conflicting way then
8:        $a_i$  must remain stopped until the intersection  $k$  becomes clear
9:     else if There is a vehicle  $a_j$  that answers the broadcast message with 0 velocity
       and  $e$  position regarding the intersection  $k$  then
10:       $a_i$  must remain stopped until the position  $e$  becomes clear to avoid blocking
        the intersection
11:     else if There is a vehicle  $a_j$  that answers the broadcast message with exactly
        the same conditions as  $a_i$  regarding the intersection  $k$  then
12:       $a_i$  and  $a_j$  apply a negotiation protocol to decide which one gets the priority
        to cross the intersection.
13:     end if
14:   end if
15: end while

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2.1 Emergency Vehicles

An emergency vehicle a_e is a vehicle that plays an emergency role (E). This vehicle has the priority of intersection crossing over the rest of vehicles. We should note that we assume only two lines in conflict way at each intersection.

In order to define the behavior of emergency vehicles is required to introduce the two radius that determine the behavior of autonomous vehicles in the DIM model: the perception radius and the communication radius. The perception radius P_i of a vehicle a_i defines a detection area inside which, other autonomous

vehicles are detected by the sensors of a_i . The communication radius C_i defines a communication area inside which, other autonomous vehicles receive messages sent by a_i . Messages can be delivered to specific receivers or can be broadcasted to any receiver inside this area.

When an emergency vehicle a_e arrives at an intersection k , this vehicle has the priority for crossing the intersection unless other vehicles are already crossing the intersection in a conflict way. To represent this behavior, a_e sends a broadcast message to those vehicles that are situated inside its communication radius C_e . In this message, a_e is identified as an emergency vehicle. According to this, the following situations may occur:

- If a_e does not receive any response to its broadcast message, then crosses the intersection with priority.
- If other vehicles are already crossing the intersection in a conflict way, the vehicle a_i that is playing the negotiator role (N) in this crossing, determines whether it can stop before arriving at the intersection. Thus, a_i reduces the velocity until stopping at the intersection, remaining stopped until a_e finishes the intersection crossing.
- If other vehicles are already waiting to cross the intersection, the vehicle a_i that is playing the negotiator role (N) broadcasts a message in order to stop the traffic in the conflict way.
- If two emergency vehicles arrive at the same time at the intersection k , each one in a different conflict way, therefore:
 1. If there are not any other vehicle already waiting at the intersection, then, both emergency vehicles take the same behavior of a negotiator role (i.e. they apply a negotiation protocol in order to take the decision about who has the crossing priority).
 2. If there are other vehicles waiting in the intersection, they follow the default behavior of a negotiator role until one of the emergency vehicles crosses the intersection.

It must be noted that emergency vehicles are only considered when they are inside the specific radius. Therefore, the flow of the global traffic system is not influenced by emergency vehicles.

3 Results

In this section we show several experiments focused on testing the performance of the emergency vehicles model. We used the SUMO simulator for urban mobility. SUMO provides functionalities to simulate traffic in cities composed by streets and intersections (Fig. 1). For the purpose of these experiments, we considered four intersections for different traffic densities, ranging from 0 to 1. Emergency vehicles may appear with a prior probability of 1 vehicle per each 3600 vehicles.

In order to test the performance of the model proposed, we compare our DIM model for emergency vehicles with a Green Wave model, which is the traditional approach that provides a traffic intersection management based on traffic lights.

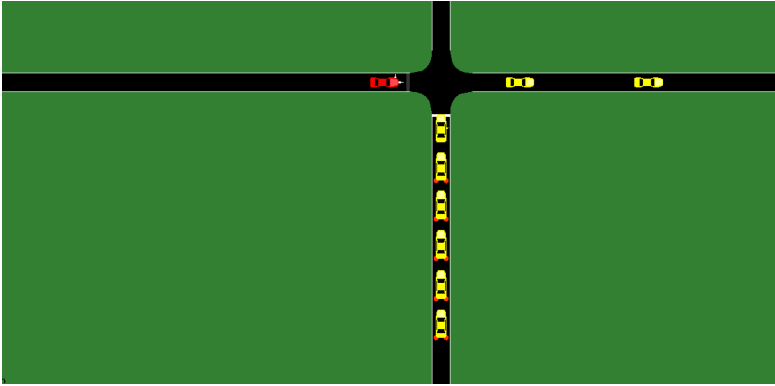


Fig. 1. SUMO simulator showing an intersection with regular vehicles (yellow) and emergency vehicles (red). (Color figure online)

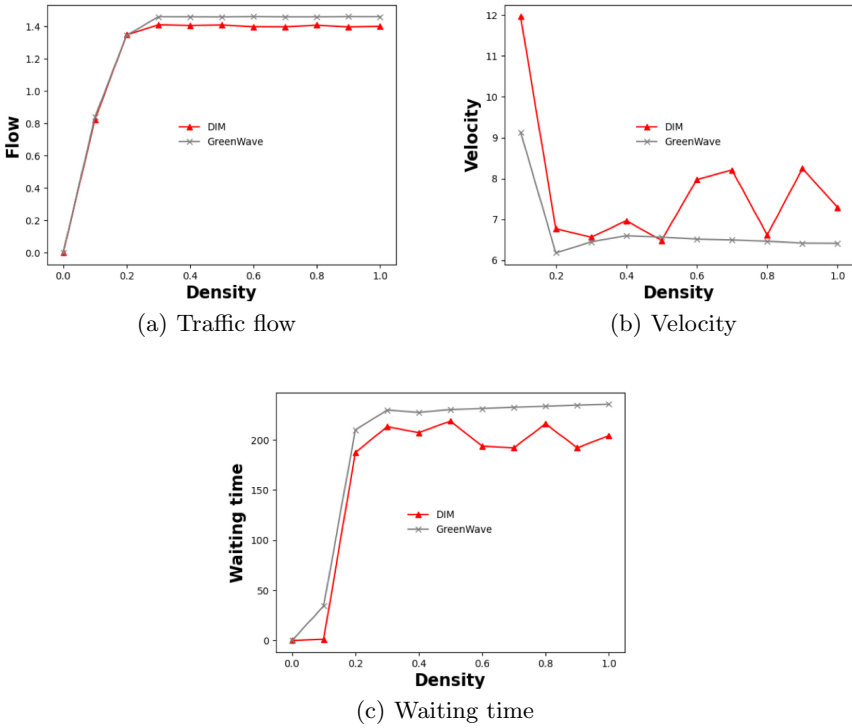


Fig. 2. Models comparison without emergency vehicles

In Fig. 2, we show the performance of both models in cities without emergency vehicles. Figure 2(a) represents the traffic flow depending on the density of the city. As it can be observed, the flow increases in both models until a density of 0.3. From this density on, the traffic flow stabilizes. This can be explained since the intersections may be blocked for large values of traffic flow.

As it can be appreciated, the performance of the Green Wave model is slightly worse than DIM. This behavior is repeated in Fig. 2(b), which shows the average velocity of vehicles and in Fig. 2(c), which shows the average waiting time. Both variables, velocity and waiting time are slightly worse for the Green Wave model. This can be explained since the DIM model provides a coordination mechanism based on the traffic, which is adapted depending on the traffic scenario. In contrast, the Green Wave considers a fixed amount of time to give crossing priorities. This strategy may penalize blocked lines.

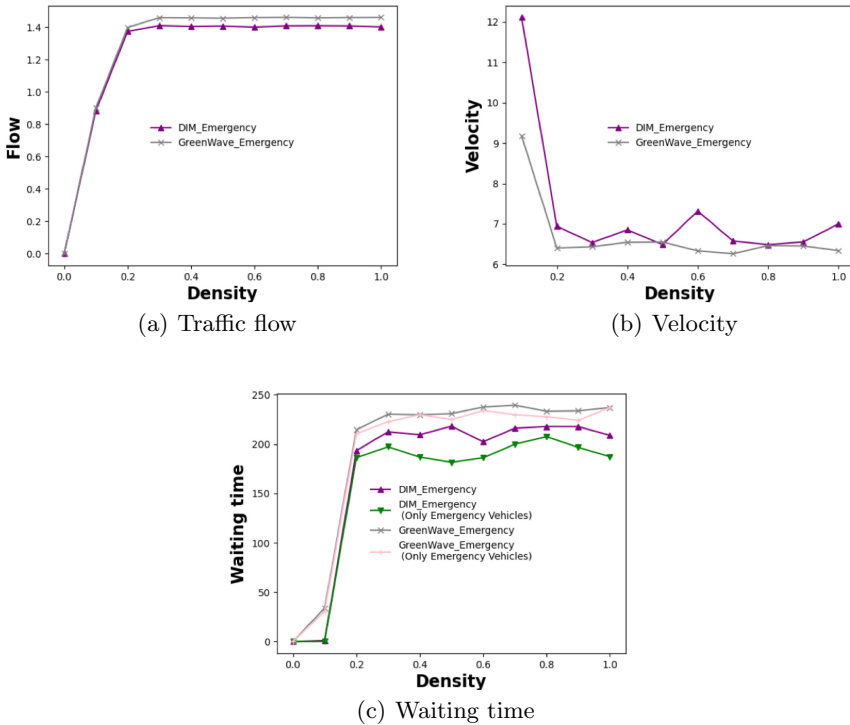


Fig. 3. Models comparison with emergency vehicles

In Fig. 3, it can be observed the performance of both models when emergency vehicles are introduced. Similar to the previous experiment, both the traffic flow and the velocity are quite stable from densities values higher than 0.2. In

Fig. 3(c) we can observe the average waiting time of emergency vehicles and the average waiting time of regular vehicles (i.e. non-emergency vehicles). As it can be observed, the Green Wave model does not give significant priority to emergency vehicles. In contrast, the DIM model provides a mechanism that allows the emergency vehicles to considerably reduce the average waiting time compared with the rest of vehicles. Moreover, these differences become significant when the traffic density is higher than 0.2.

4 Conclusions

Intersections represent point of conflict since autonomous vehicles from different lines need to cross. Centralised solutions provide coordination mechanisms in order to determine priorities for crossing. In addition, emergency vehicles are required to get the highest priority as possible when crossing the intersection. Therefore, distributed solutions that can adapt to changes in the environment (such as, traffic densities) are required.

In this paper, we propose a distributed coordination management system that considers emergency vehicles. This system provides crossing mechanisms at intersections in a distributed fashion. According to the experiments, this model provides a better performance than other centralised approaches managed by traffic lights regarding variables such as traffic flow, velocity and waiting time. What is more, this performance is eventually better for emergency vehicles that require highest priorities than the rest of vehicles.

One assumption of our work is the consideration of one-way lines. In future works, we plan to extend this approach in order to consider several lines for each direction. This would be specially interesting when emergency vehicles are considered.

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