A Multi-Agent Framework for Dynamic Traffic Management Considering Priority Link

Abdelouafi Ikidid[1], Abdelaziz El Fazziki[2] and Mohamed Sadgal[3]

[123]Computer Science Department, Laboratory ISI, Cadi Ayyad University, Morocco

***Abstract*:** To favor emergency vehicles, promote collective modes of transport in Moroccan cities, we propose in this paper a control system to manage traffic at signalized intersections with priority links in urban settings. This system combines multi-agent technology and fuzzy logic to regulate traffic flows. The traffic system flow is divided into two types of vehicles: priority and regular vehicles. The regular vehicles can use only the regular links, while the priority vehicles may use both priority and the regular links. This approach aims to favor emergency vehicles and promote collective modes of transport, it acts on the traffic light phases length and order to control all traffic flows. We proposed a decentralized system of regulation based on real-time monitoring to develop a local inter-section state, and intelligent coordination between neighboring intersections to build an overview of the traffic state. The regulation and prioritization decisions are made through cooperation, communication, and coordination between different agents. The performance of the proposed system is investigated and instantiated in ANYLOGIC simulator, using a section of the Marrakesh Road network that contains priority links. The results indicate that the designed system can significantly develop the efficiency of the traffic regulation system.

***Keywords*:** Fuzzy Logic, Multi-agent modelization, Priority vehicles, Priority links.

1. Introduction

In the decades to come, transport systems will be a major challenge in ensuring people's movements and mobility. Indeed, the increasing population and urbanization and the decreasing cost of vehicles impose a progressive overload on the transport infrastructure. In modern cities, the majority of the road network contains a special road link for tramway and priority vehicles. Promoting the use of public transport can significatively increase infrastructure capacity and alleviate the congestion phenomenon. In this paper, we combine agent technology and fuzzy logic to build a cooperative real-time traffic signal regulation system, where the signal control plan is recurrently updated to prioritize all the priority vehicles using the special link.

Urban traffic management is characterized by data with a high level of uncertainties and a large number of contributed actors, that make its management very imbricated and distributed. According to [1] the traffic has increased by 3% In Morocco between 2016 and 2017 in urban areas. Consequently, the road infrastructure will have more demands and more overload. Optimizing the management and exploitation of urban road infrastructure is one of the suitable solutions to reduce this overload. This optimization includes the rationalization of traffic light control to prioritize priority vehicles. We mean by priority vehicles the set of transport modes that assures mass mobility of people or nominated and allowed to react to emergency cases.

Traffic light regulation that takes into consideration priority vehicles is at the dept of intelligent transport systems (ITS) research field. Artificial intelligence is widely used to reach an efficient ITS [2]. In this paper, we develop a decentralized multi-agent system (MAS) to regulate Traffic Signal Control System (TSCS) and prioritize the priority vehicles. The proposed system is based on fuzzy logic to deal with the uncertainty of traffic road data. It aims to reduce travel time and promote the use of public transport modes.

The rest of the paper is organized as follows: Section 2 describes the proposed system and the methodology used. Section 3 presents the implementation phase of the used methodology and investigates the performance of our proposed system. Finally, section 4 summarizes the results of the approach and states some future work.

2. Related Works

The ITS incorporate artificial technologies to overcome the congestion challenges and other transportation issues that are difficult to address using traditional computational techniques. The widely used artificial intelligence techniques for optimizing traffic signals are Artificial Neural network System [3][4], Deep Learning [5][6][7], Genetic Algorithm[8] [9], Fuzzy logic (FL) [10], Multi-Agent System (MAS)[11], Case-Based Reasoning [12] and Ant Colony Algorithm[13]. These methods are used to handle diverse problems, e.g., traffic congestion[14], incident detection[15], and route guidance [16]. Since the traffic system is characterized by uncertainty, fuzzy and inexact data, and wide-reaching distributed architecture, in this paper, we propose a multi-agent system that uses agent fuzzy logic to design a cooperative real-time traffic signal optimization system, where the signal control plan is frequently updated to meet the unpredictable traffic conditions.

Pre-timed signal control cannot adapt to the non-stationary traffic state. It has been a while since interactive system control became a trend in traffic management. The first appearance of adaptative traffic control was in the last decade of the second millennium, with the release of the cycle and offset optimization technique (SCOOT) in the 1980s, the Sydney cooperative adaptive traffic system (SCATS), and the green link determining (GLIDE) system. Thereafter, these adaptative control systems were implemented in many countries to manage traffic control in metropolitan areas, and others have been developed, such as RHODES [17] and TUC [18].

The MAS is rapidly growing as one of the most powerful popular technologies proposed to solve complicated problems in different fields, such as electrical engineering, cloud security [19][20], data storage[21], civil engineering, and transportation systems.

Computer technologies, including MAS, have been widely proposed to deal with traffic control and management [22]. These technologies have been implemented in different levels and components of the transport system such as traffic signal control [23] [24], vehicles and their drivers [25], highways [26], and have proved a notable performance. Another approach investigates the public transport priority [27].

The agent technology treated the traffic management problem as a distributed system. It proposed to solve this problem in a distributed manner. Case-based reasoning was proposed in [25] for the traffic signal control; the agents monitor the state of the traffic conditions at an intersection and select a solution to use from its cases-base. Another study offers intermodal regulation strategies to promote a public mode of transport [28].

3. Methodology

To build an agent system, and like any software, an engineering process must be respected, namely, Agent-Oriented Software Engineering (AOSE). It aims to present the development process of an agent-based approach, as well as the acquired features brought by using the agents to the deployment systems (for surveys see [29] [30]). To develop our proposed system, we propose an increasingly detailed model from abstract to a concrete aspect. This simple model consists of five-stage as shown in Fig.1.

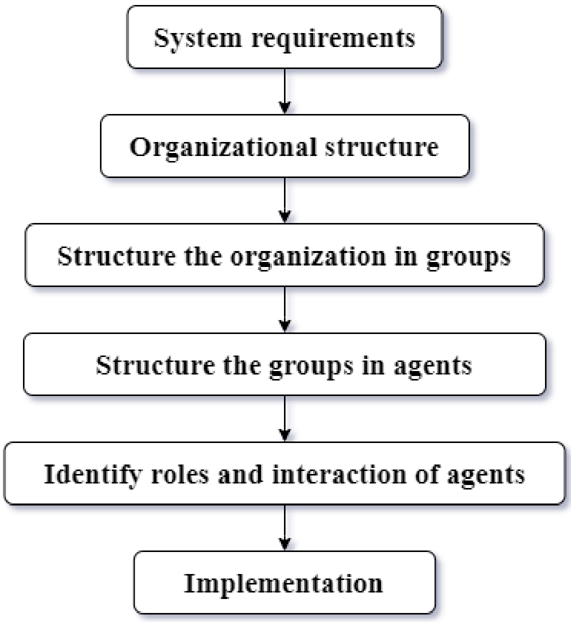

Figure 1. Development process model

3.1 System requirements

The requirement stage aims to define the system components, their functions, and interactions, and to describe the scenario under study. Our system requirement phase has three tasks: (1) intersection network modeling, (2) traffic light control components, (3) scenario description.

3.1.1 Multi-Intersections network modeling

The idea consists of extending the TSCS to prioritize the priority vehicles. The urban road network is viewed as a strongly connected oriented graph $N = (I, A)$, where I is the set of nodes that represents the intersection, and A is the set of the arcs which connects these intersections. We have two types of arcs; priority arcs which represent the priority links and regular arcs which represent the regular link. We assume that to control an intersection we have to take into consideration upstream and downstream flows. Therefore, each arc has a set of successors $succ(A_{ij}) = \{ A_{jk}, (i,j,k) \in I \}$ and a set of predecessor arcs $pred(A_{ij}) = \{ A_{ki}, (i,j,k) \in I$. Fig. 2 represents an intersection of two regular roads and two priority roads.

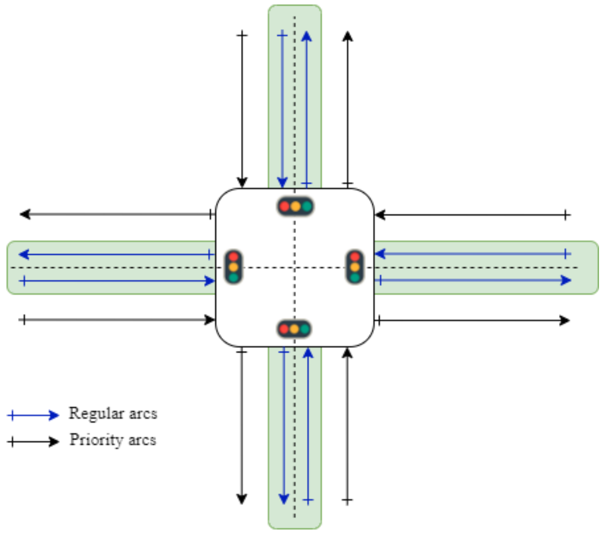

Figure 2. Intersection of two ordinary roads and two priority roads

3.1.2 Traffic light control components

The junction in the system is a signalized intersection, an intersection is managed by an intersection control unit (ICU). The urban road traffic model is made up of:

ArcMonitor: each incoming arc is monitored by an ArcMonitor; the monitoring process consists of collecting the data from sensors to define the arc traffic parameters (table 1), and calculate arc state factors. These factors are the stop ratio (SR) (equation 1) and the congestion ratio (CR) (equation 2) when the signal is red at the arc stop line, while the arc state factors are CR and congestion ratio at arc successor's (CRs) when the signal is green. The SR represents the waiting time ratio in the arc, and the *CR* is the ratio of enqueued vehicles over the capacity of the arc.

Table 1. Arc traffic parameters

Parameter	Definition
T_{max}	the maximum concentration of vehicles in the arc
T_t	the concentration at an instant t
t_s	the vehicle stop time on the red signal
t_y	the yellow signal length
c	the cycle length

$$SR = \frac{t_s}{c - ty} \quad (1)$$

$$CR = \frac{T_t}{Tmax} \quad (2)$$

Phases manager: the ICU contains one phase manager and it defines the urgency level of red phases and the priority level of the current green phase. A phase is represented by the arc with the highest state factors. The phase's urgency and priority levels are obtained by the fuzzy mechanism presented in [14]. The phase with maximal urgency level will be proposed as a candidate for next green time.

Controller: the controller is the axis component of the traffic light control. It defines the cycle layout (phase sequence and length). The controller decides, via fuzzy inference, to either extend the current green phase or switch to the candidate one.

Coordinator: the main role of the coordinator is to coordinate with the neighboring intersections and exchange local stat data to develop an overview of the environment. Additionally, it stores after each cycle, the intersection data decision series to build a case-decision base which will be used in the system failure case. Fig. 3 represents the components of the generic TSCS.

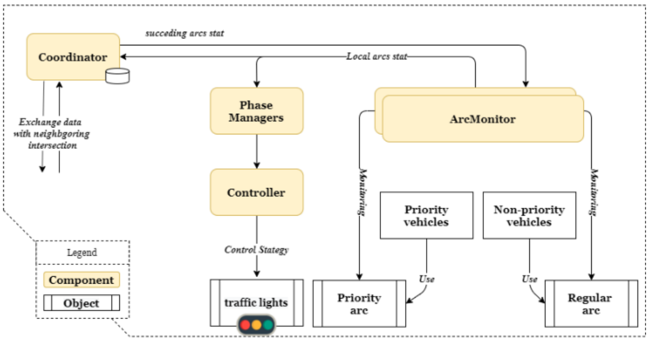

Figure 3. The components of the generic TSCS

3.1.3 Scenario description

The system uses the traffic signal plan to prioritize the priority arcs. It updates the phase layout during system operation by decides when to interrupt the current green phase and which phase will replace it. It also creates a cases-base decision that contains the history of traffic environment conditions and corresponding decisions.

The components presented in Fig.3 are tasked to elaborate a traffic light strategy, respecting a set of constraints and functional exigences.

- The regulation process is initialized after each recurring interval with a group of phases P { Pr, Pp }, where Pr represents a phase set of regular arcs, and the Pp represents the phase set of priority arcs.
- All the arcs are monitored to collect state data. The indicators of traffic conditions of each arc are defined by observing the local state, and by considering the traffic state at succeeding arcs.
- During the cycle, if the degree of saturation in the succeeding arc is intolerable, the preceding arc urgency is reduced, retarding evacuation and relieve saturation.
- The candidate phase for green time will be chosen from the priority phase with at least one enqueued vehicle. If all priority phases are empty, we choose it from regular phases.
- All types of phases have the right of green time one and one time only in the cycle, except those phases with no enqueued vehicles at their arcs can waive their turn.
- No phase can get the green time twice in the same cycle.
- The control strategy consists of phase sequence and timing
- The pedestrian phase is outside of the scope of our approach.

3.2 The organizational structure

The selection of the organizational structure is a very essential stage in MAS development. It defines the general structure of roles, interactions, and authority that govern the system behaviors and entities' relationships. Several MAS organizational structures have been proposed over the years, a survey is presented in [31] [32].

To build a federation organization that contains a set of groups we refer to the AGR (agent, group, and role) model. Therefore, we use the metamodel of AALAADIN [33]. Fig 4 depicts a representative diagram of this model. In our case, we assume the notion of belonging to a group is limited to only one group.

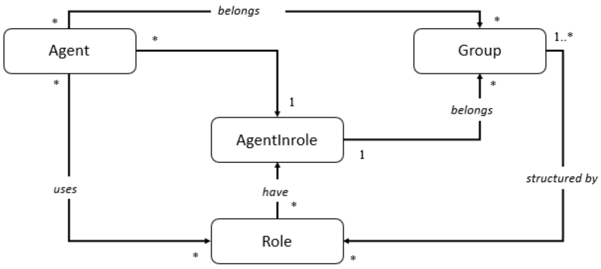

Figure 4. Organizational structure

3.2.1 Structure the organization into groups

The multi-intersection network is decomposed into regions controlled by ICU, which coordinate with neighboring control units through communication. The ICU corresponds in MAS to an Intersection Control Group (ICG). Each ICG was assigned to an intersection and charge with full control over the local flows.

The proposed multi-agent system has a decentralized architecture, where the ICGs are structured in federations organization. The federation organization represents a system with a group of agents. Group members have common goals and a single delegate that represents the group. They can interact directly between them, or with the external environment through the delegated agent. The group is capable of making its own decisions collaboratively between group members, and without any central supervising agent. Fig. 5 depicts a network with 3 intersections and their corresponding control groups.

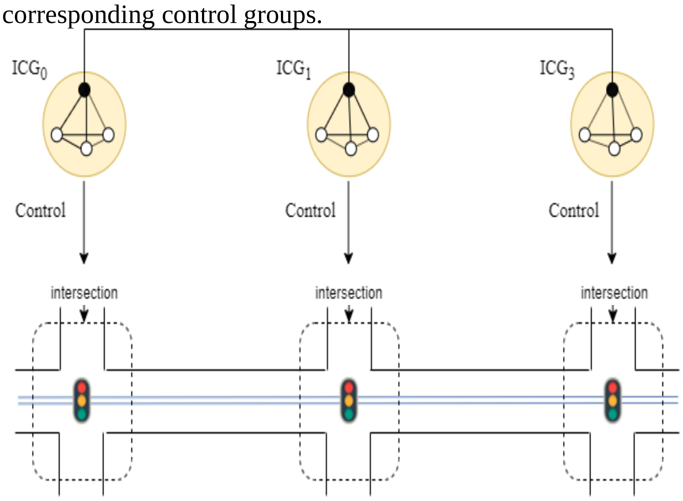

Figure 5. Example of 3 intersections and their control groups

3.3 Structure the groups into agents.

To define the group members of the ICG, we will use the one-to-one mapping between TSCS components and MAS. Therefore, each active component at the regulation system will be presented by an agent. The agent fulfills a specific role in the system, this specification improves the agent's adaptability and efficiency in the requested role. We will use a UTS/MAS alignment as shown in Table 2. The ICU is presented by an Agent Control Group (ACG). Each ACG includes many agents classified in four types: an ArcMonitor Agent associated with each incoming arc, one Phases Manager Agent, a Controller Agent, and a Coordinator Agent. Table 2 illustrates the different types of agents and their roles.

Table 2. TSCS /MAS alignment

UTC components	MAS	Roles
ArcMonitor	ArcMonitor agent	• On-line monitoring the arc traffic state. • Provides the traffic state factors.
Phases manager	Phases manager agent	• Controls the phase sequences. • Defines urgency and priority of phases • Selects a phase candidate for the next green time.
Controller	Controller agent	• Regulates phase layout • Timely updating the signal control plan.
Coordinator	Coordinator agent	• Coordinates with the neighboring ICG. • Plays role in all extern communications. • Shares the local. • Saves decisions' conditions

3.4 Identify roles and interaction of agents

The proposed system contains a set of ACG. Each ACG is assigned to s signalized intersection with a priority link. Agents attempt to fulfill their roles required by the group goal. Coordination is attempted between the agents' groups by exchanging data and predetermined interactions. Each agent seeks to accomplish its own goals taking into consideration the goals of the other agents and group. The goals and roles of each agent are presented as follow:

3.4.1 ArcMonitor agent

This kind of agent is assigned to each incoming arc. Its goal is to on-line monitor the arc traffic state. Afterward, it provides the traffic state factors to phases manager agent and coordinator agent. The successor arc state factors are obtained through collaboration with the coordinator agent.
The arc state factors differ according to the light signal state at the arc stop line. Thus, when the signal is red, the state factors are the stop ratio (SR), congestion ratio (CR), and congestion ratio of downstream (CRd). While these factors are the CR and CRd when the signal is green. The linguistic variables, as well as the membership functions of variables SR, CR, and CRd, are standardized as shown in Fig. 6 there are four membership functions, including Small (S), Medium (M), Large (L), and Very Large (VL).

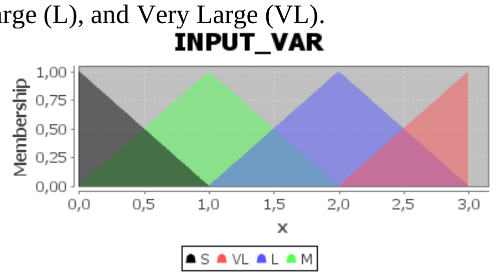

Figure 6. Membership function and linguistic of state variables.

3.4.2 Phases manager agent

The phases manager agent controls the phase sequences. It selects a phase to be a candidate for the next green time. Phases with priority arc are promoted and suggest first to next green time. This agent defines urgency and priority through the fuzzy mechanism. Thereafter, provides results to the controller agent. The linguistic variables and membership functions of variables urgency and priority are presented in fig.7 (a) and fig.7 (b) respectively.

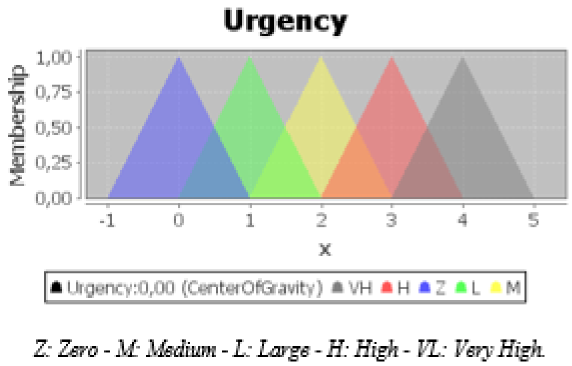

Figure 7 (a)

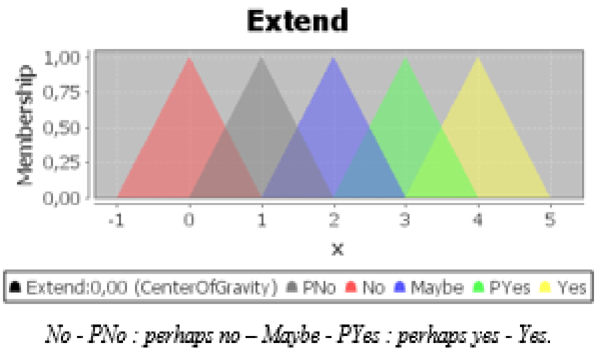

Figure 7 (b)

Figure 7. Membership function and linguistic of Urgency and Extend variables

3.4.3 Controller agent

The objective of this agent is to regulate phase layout by timely updating the signal control plan. The update decision is made collaboratively and aims at giving priority to priority arc, and also optimize management of other traffic flows. The linguistic variables and membership functions of the decision variable are presented in Fig.8.

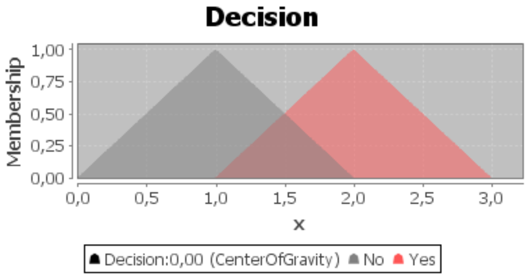

Figure 8. Membership function and linguistic of the decision variable.

3.4.4 Coordinator agent

The objective of this agent is to coordinate with the neighboring ACG. It represents the communication interface of the group by playing a mediator role in all extern communications. The coordinator agent shares the local state of incoming arcs with the adjacent coordinator agents. In case of failure, it suggests an alternative traffic signal plan.

Fig. 9 shows an overview of the proposed multi-agent system, along with the different agent's interactions.

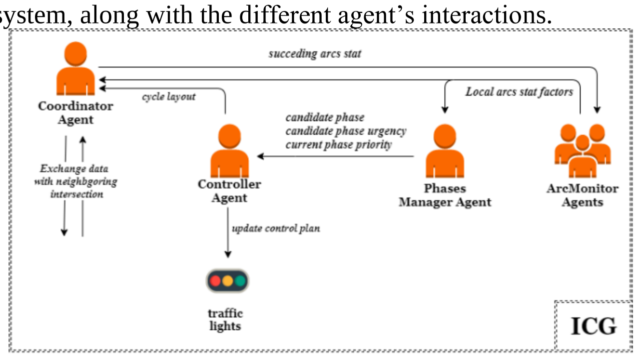

Figure 9. Overview of agent's interaction.

4. Experimental result and performance analysis

To show the performance of the proposed system, we instantiate the proposed system in the AnyLgic simulator. AnyLogic is a Java-based development environment that includes a graphical model editor and code generator. We use the JFuzyLogic library to represent the fuzzy inference system. The simulation uses a section of the Marrakesh road network. This section contains a priority link used for electric buses and emergency vehicles. Fig. 10 describes the representation of different intersection agents during the simulation model.

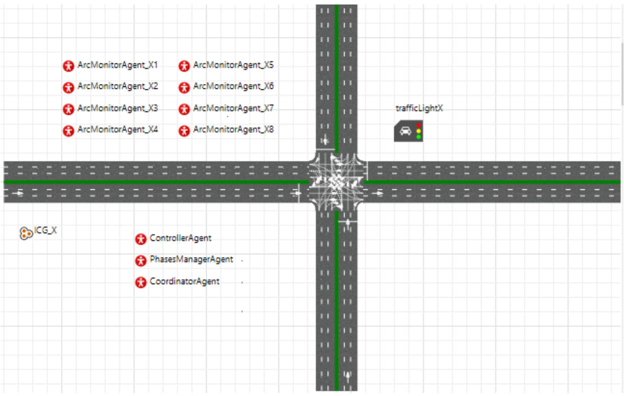

Figure 10. Representation of an intersection during the simulation

To investigate the performance of our proposed system, we use the travel time as mean evaluating criteria. The travel time is the elapsed time between the starting of the vehicle from the start-point and arriving at the stop-point.

Two types of traffic signal control approaches are used to conduct a comparative analysis with the proposed method TSCS (method3), namely fixed-time controller (method1) and the current system control without agents(methpd2). all control methods are tested on similar conditions and under 3 different scenarios: the first scenario allows the assessment of the performance of methods under low traffic demand. The second scenario describes medium traffic demand and represents a moderate congestion situation. The third scenario provides results for high traffic demand. Each case is repeated for 20 iterations to increase the reliability of the collected data.

Fig. 11 depicts the average travel time of all vehicle types and for each traffic condition scenario. It particularly shows that our proposed approach allows the fastest travel time under all scenarios.

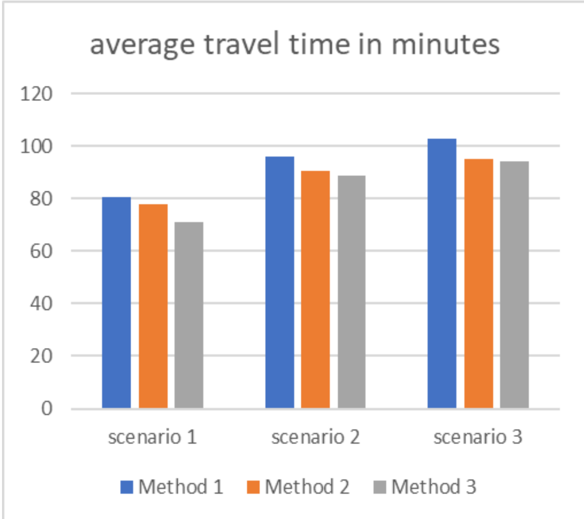

Figure 11. Average travel time

The travel time of priority vehicles in our system has also been compared with travel time in perfect stationary conditions (SC). We mean by ST, the situation where the priority vehicles surpass all intersections without stopping in any stop-line and with a fixed speed. Otherwise, the travel stop time is null. Fig.12 shows the travel time in 3 different scenarios. The first with stationary conditions (ST). The second represents our approach where the priority is taken into consideration.

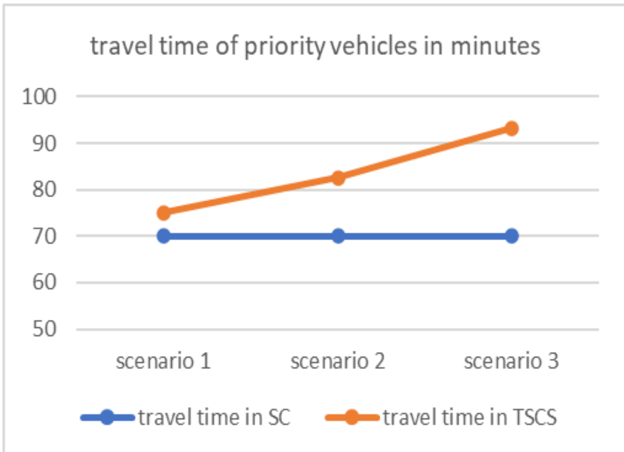

Figure 12. Travel time of priority vehicles.

The results showed that the strategy based on the priority link transport using multi-agent technology and fuzzy logic gives a reduced travel time and very close to the travel time in perfect conditions.

5. Conclusion

In this paper, we have presented a fuzzy logic-supported multi-Agent system for urban traffic and priority link control. This proposal aims to promote the use of public transport and fluidize the emergency traffic flow. The agents communicate to decide in real-time and cooperatively the optimized traffic light plan. There are two levels of cooperation, the inter-junction, and intra-junction, to avoid local optimization and develop a control plan that takes into consideration all neighboring intersections

The proposed system has been simulated in an Anylogic simulator. The obtained results show that the use of the multiagent organization has generated significant improvement in the travel time of the traffic network. Besides, our proposed system enhances significatively the travel time of priority vehicles in different traffic road conditions. Nevertheless, future research should study the recommendation path and explore the case of system failure.

References

[1] M. Ministry of Equipment Transport and Logistics-Morocco, “Recueil du Trafic Routier 2017,” 2017.

[2] J. Garcia-Nieto, J. Ferrer, and E. Alba, “Optimising traffic lights with metaheuristics: Reduction of car emissions and consumption,” *Proc. Int. Jt. Conf. Neural Networks*, pp. 48–54, 2014, doi: 10.1109/IJCNN.2014.6889749.

[3] X. Ma, Z. Dai, Z. He, J. Ma, Y. Wang, and Y. Wang, “Learning traffic as images: A deep convolutional neural network for large-scale transportation network speed prediction,” *Sensors (Switzerland)*, vol. 17, no. 4, 2017, doi: 10.3390/s17040818.

[4] E. Doğan and A. P. Akgüngör, “Forecasting highway casualties under the effect of railway development policy in Turkey using artificial neural networks,” *Neural Comput. Appl.*, vol. 22, no. 5, pp. 869–877, 2013, doi: 10.1007/s00521-011-0778-0.

[5] C. Chen, B. Liu, S. Wan, P. Qiao, and Q. Pei, “An Edge Traffic Flow Detection Scheme Based on Deep Learning in an Intelligent Transportation System,” *IEEE Trans. Intell. Transp. Syst.*, vol. 22, no. 3, pp. 1840–1852, 2021, doi: 10.1109/TITS.2020.3025687.

[6] M. Veres and M. Moussa, “Deep Learning for Intelligent Transportation Systems: A Survey of Emerging Trends,” *IEEE Trans. Intell. Transp. Syst.*, vol. 21, no. 8, pp. 3152–3168, 2020, doi: 10.1109/TITS.2019.2929020.

[7] H. Nguyen, L. M. Kieu, T. Wen, and C. Cai, “Deep learning methods in transportation domain: A review,” *IET Intell. Transp. Syst.*, vol. 12, no. 9, pp. 998–1004, 2018, doi: 10.1049/iet-its.2018.0064.

[8] T. Shen, K. Hua, and J. Liu, “Optimized Public Parking Location Modelling for Green Intelligent Transportation System Using Genetic Algorithms,” *IEEE Access*, vol. 7, pp. 176870–176883, 2019, doi: 10.1109/ACCESS.2019.2957803.

[9] M. S. Ghanim and G. Abu-Lebdeh, “Real-Time Dynamic Transit Signal Priority Optimization for Coordinated Traffic Networks Using Genetic Algorithms and Artificial Neural Networks,” *J. Intell. Transp. Syst. Technol. Planning, Oper.*, vol. 19, no. 4, pp. 327–338, 2015, doi: 10.1080/15472450.2014.936292.

[10] N. Kumar, S. S. Rahman, and N. Dhakad, “Fuzzy Inference Enabled Deep Reinforcement Learning-Based Traffic Light Control for Intelligent Transportation System,” pp. 1–10, 2020.

[11] R. Sathiyaraj and A. Bharathi, “An efficient intelligent traffic light control and deviation system for traffic congestion avoidance using multi-agent system,” *Transport*, vol. 35, no. 3, pp. 327–335, 2020, doi: 10.3846/transport.2019.11115.

[12] O. Quirion-Blais and L. Chen, “A case-based reasoning approach to solve the vehicle routing problem with time windows and drivers’ experience,” *Omega (United Kingdom)*, no. xxxx, p. 102340, 2020, doi: 10.1016/j.omega.2020.102340.

[13] X. Guo and Y. Liu, “Intelligent traffic cloud computing system based on ant colony algorithm,” *J. Intell. Fuzzy Syst.*, vol. 39, no. 4, pp. 4947–4958, 2020, doi: 10.3233/JIFS-179980.

[14] A. Ikidid and E. F. Abdelaziz, “Multi-Agent and Fuzzy Inference Based Framework for Urban Traffic Simulation,” in *Proceedings - 2019 4th International Conference on Systems of Collaboration, Big Data, Internet of Things and Security, SysCoBIoTS 2019*, 2019, doi: 10.1109/SysCoBIoTS48768.2019.9028016.

[15] A. B. Nikolaev, Y. S. Sapego, A. N. Jakubovich, L. I. Berner, and V. Y. Stroganov, “Fuzzy algorithm for the detection of incidents in the transport system,” *Int. J. Environ. Sci. Educ.*, vol. 11, no. 16, pp. 9039–9059, 2016.

[16] J. Wu, B. Chen, K. Zhang, J. Zhou, and L. Miao, “Ant pheromone route guidance strategy in intelligent transportation systems,” *Phys. A Stat. Mech. its Appl.*, vol. 503, pp. 591–603, 2018, doi: 10.1016/j.physa.2018.02.046.

[17] P. Mirchandani and L. Head, “A real-time traffic signal control system: Architecture, algorithms, and analysis,” *Transp. Res. Part C Emerg. Technol.*, vol. 9, no. 6, pp. 415–432, 2001, doi: 10.1016/S0968-090X(00)00047-4.

[18] C. Diakaki, M. Papageorgiou, and K. Aboudolas, “A multivariable regulator approach to traffic-responsive network- Wide signal control,” *Control Eng. Pract.*, vol. 10, no. 2, pp. 183–195, 2002, doi: 10.1016/S0967-0661(01)00121-6.

[19] M. El Ghazouani, M. A. El Kiram, and L. Er-Rajy, “Blockchain & multi-agent system: A new promising approach for cloud data integrity auditing with deduplication,” *Int. J. Commun. Networks Inf. Secur.*, vol. 11, no. 1, pp. 175–184, 2019.

[20] M. El Ghazouani, M. A. El kiram, E.-R. Latifa, and Y. El Khanboubi, “Efficient Method Based on Blockchain Ensuring Data Integrity Auditing with Deduplication in Cloud,” *Int. J. Interact. Multimed. Artif. Intell.*, vol. 6, no. 3, p. 32, 2020, doi: 10.9781/ijimai.2020.08.001.

[21] Y. El Khanboubi and M. Hanoune, “Exploiting Blockchains to improve Data Upload and Storage in the Cloud,” vol. 11, no. 3, pp. 357–364, 2019.

[22] P. G. Balaji and D. Srinivasan, “Type-2 fuzzy logic based urban traffic management,” *Eng. Appl. Artif. Intell.*, vol. 24, no. 1, pp. 12–22, 2011, doi: 10.1016/j.engappai.2010.08.007.

[23] A. Ikidid and A. El Fazziki, “Multi-agent based traffic light management for privileged lane,” *8th Int. Work. Simul. Energy, Sustain. Dev. Environ. SESDE 2020*, pp. 1–6, 2020, doi: 10.46354/i3m.2020.sesde.001.

[24] A. L. C. Bazzan, “A Distributed Approach for Coordination of Traffic Signal Agents,” *Int. Conf. Auton. Agents Multi-Agent Syst.*, vol. 10, no. 1, pp. 131–164, 2005, doi: 10.1007/s10458-004-6975-9.

[25] Xiao Xiong Weng, Shu Shen Yao, and Xue Feng Zhu, “Architecture of multi-agent system for traffic signal control,” no. December, pp. 2199–2204, 2005, doi: 10.1109/icarcv.2004.1469507.

[26] K. Teknomo, “Application of microscopic pedestrian simulation model,” *Transp. Res. Part F Traffic Psychol. Behav.*, vol. 9, no. 1, pp. 15–27, 2006, doi: 10.1016/j.trf.2005.08.006.

[27] M. Tlig and N. Bhouri, “A multi-agent system for urban traffic and buses regularity control,” *Procedia - Soc. Behav. Sci.*, vol. 20, pp. 896–905, 2011, doi: 10.1016/j.sbspro.2011.08.098.

[28] N. Bhouri, P. Lotito, N. Bhouri, and P. L. Régulation,

"Régulation du trafic urbain multimodal avec priorité pour les transports en commun," 2017.

[29] O. Z. Akbari, "A survey of agent-oriented software engineering paradigm: Towards its industrial acceptance," *Int. J. Comput. Eng. Res.*, vol. 1, no. 2, pp. 14–28, 2010.

[30] M. Cossentino, N. Gaud, V. Hilaire, S. Galland, and A. Koukam, "ASPECS: An agent-oriented software process for engineering complex systems," *Auton. Agent. Multi. Agent. Syst.*, vol. 20, no. 2, pp. 260–304, 2010, doi: 10.1007/s10458-009-9099-4.

[31] A. Dorri, S. S. Kanhere, and R. Jurdak, "Multi-Agent Systems: A Survey," *IEEE Access*, vol. 6, pp. 28573–28593, 2018, doi: 10.1109/ACCESS.2018.2831228.

[32] B. Horling and V. Lesser, "A survey of multi-agent organizational paradigms," *Knowl. Eng. Rev.*, vol. 19, no. 4, pp. 281–316, 2004, doi: 10.1017/S0269888905000317.

[33] O. Gutknecht and J. Ferber, "Un meta-modèle organisationnel pour l'analyse, la conception et l'exécution de systèmes multi-agents," *Journées Francoph. pour l'Intelligence Artif. Distrib. les Systèmes Multi-Agents 1999*, 1999.