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Optimizing urban traffic control using a rational agent

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Abstract: This paper is devoted to developing and evaluating a set of technologies with the objective of designing a methodology for the implementation of sophisticated traffic lights by means of rational agents. These devices would be capable of optimizing the behavior of a junction with multiple traffic signals, reaching a higher level of autonomy without losing reliability, accuracy, or efficiency in the offered services. In particular, each rational agent in a traffic signal will be able to analyze the requirements and constraints of the road, in order to know its level of demand. With such information, the rational agent will adapt its light cycles with the view of accomplishing more fluid traffic patterns and minimizing the pollutant environmental emissions produced by vehicles while they are stopped at a red light, through using a case-based reasoning (CBR) adaptation. This paper also integrates a microscopic simulator developed to run a set of tests in order to compare the presented methodology with traditional traffic control methods. Two study cases are shown to demonstrate the efficiency of the introduced approach, increasing vehicular mobility and reducing harmful activity for the environment. For instance, in the first scenario, taking into account the studied traffic volumes, our approach increases mobility by 23% and reduces emissions by 35%. When the roads are managed by sophisticated traffic lights, a better level of service and considerable environmental benefits are achieved, demonstrating the utility of the presented approach.

Key words: Rational agents, Traffic light control, Optimization, Traffic mobility
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1 Introduction

In recent years, road traffic has become an essential part of a modern city. Research in the field of optimizing traffic-volume arteries has become one of the most pursued topics (Huang *et al.*, 2012). The development of intelligent traffic systems is a transcendent challenge because the number of users on the roads constantly grows and resources that modulate the traffic flow have a set of well-identified deficiencies. In this sense, intelligent systems have proven to be computational tools that cover substantially diverse research areas because of their decision-making paradigm based on reasoning processes. For instance, improving traffic-flow will increase the service provided by the roads and reduce traffic jams, and thus has positive effect on the environment and economy (Wen, 2008). Some researchers have shown that these models produce realistic behavior (Ngai and Riggins, 2008; Chen and Cheng, 2010; Pérez *et al.*, 2010; Saeed *et al.*, 2011). In some cases, users experience long periods of time in one trip because the traffic is controlled by traffic lights that use a non-suitable scheduling for the requirements of the roads. Therefore, the implementation of modern sensors and optimization algorithms to reach an adequate cycle programming of the traffic lights might be beneficial for the road. The optimization of traffic light switching can improve the vehicular flow and avoid traffic jams. Traffic light control is a complex optimization problem, and several intelligent algorithms such as fuzzy logic, evolutionary algorithms, and reinforcement learning have already been used in attempts to solve it. This paper describes a model-based rational multi-agent architecture to control traffic lights. The presented approach introduces a

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methodology capable of making flexible and autonomous decisions for the calibration of the length of the cycles. In this paper we propose a system composed of five modules: traffic simulator, infrastructure module, communication module, decision module, and analyzer module. In fact, each module works using a different engineering perspective. Two submodules, a vehicle generator and an intersection configurator, integrate the traffic simulator layer. The infrastructure module is dedicated to assigning an operator to each intersection. The communication module facilitates the exchange of information among operators. In particular, this phase is devoted to facilitating the interaction among operators by performing a modification of the KQML language (Finin *et al*., 1993). Such communication is a process where the operators are ready to interact with others so as to generate sure commitments, which provides some extra time for their cycle. The decision module implies a rational process aiming to provide operators with a decision-making structure capable of reaching useful actions to improve the performance at any intersection. To evaluate the efficiency of our proposal, we present two cases and their results using a simulation tool developed for the project. Trends, conclusions, and future work are presented at the end of the paper to emphasize the advantages and usefulness of this promising approach.

2 Agent-based systems

Currently, one of the main goals in the artificial intelligence community is to develop theories, models, and systems to analyze and adapt the reasoning skills of a cognitive entity in order to improve their behavior. In such a case, agent-based systems have become one of the most studied topics. Despite the promising results with these systems, there are still issues that must be standardized to endow entities with more suitable operative functions. Jennings *et al.* (1998) attempted to provide 'order and coherence' in the field of agent technologies. This work is one of the main promoters of the development and deployment of agent technology. It is indicated that this technology has the ability to empower itself in a wide range of tasks. In light of this, some productive sectors have experienced a radical technological change in which the management of information technology has revolutionized its productivity, as in Regli *et al.* (2009), where the requirement of certain manufacturing systems has been claimed by the implementation of a new generation of production process, to adapt itself to uncertain situation and flexibility. Based on several studies conducted by the National Research Council, it has been possible to identify six 'grand' challenges in manufacturing, among which two stand out: (1) the use of information as a source for making successful decisions; (2) the ability of dynamical reconfiguration (Malveau and Mowbray, 2001). According to this, Nestinger *et al*. (2010) presented a mobile agent-based framework. Through this research, the authors introduced an intelligent agent which allows dynamic execution of tasks using certain algorithms of control within a manufacturing system. This paper introduces a mobile agent system called Mobile-C (www.mobilec.org), which uses Ch, an embeddable interpretive C/C++ environment. To demonstrate the performance of this proposal, some experiments were carried out during the implementation of different tasks in an automated cell, which is composed of a Puma 560, an IBM 7575, and a conveyor system. The experiment results highlight the great utility of agent technology over any other automated control subsystem. To enhance the usefulness of agent technology in performing tasks in the manufacturing sector, positive results can be found in Chan and Zhang (2002), D'Amours *et al*. (2007), Huang *et al*. (2007), Kaihara (2008), and Trappey *et al*. (2009).

The evolution of simulation and modeling techniques based on the intelligent agents has become an emerging and suitable framework, commonly employed to generate models based on social systems, which aim to achieve an evolving understanding of social phenomena. This is another example of the wide range of tasks, which are benefitting from the agent-based computing paradigm (Singh and Gupta, 2009). Agent-based modeling systems have become a trend for the study of social interactions, allowing the control of the emergent behavior of an intelligent entity. Several studies on these approaches can be found in Epstein (2007). Zhang and Li (2010) introduced how to adapt agent-based modeling and simulation (ABMS) in open and complex scenarios by modeling pattern-oriented strategies. To reach the prior idea, the strategies are generated by agent information. Such implementation is used to build a simulated environment prototype representing certain requirements and constraints in a forest fire scenario within a set of experiments. The results highlight the effectiveness of ABMS applied in open environments. Other examples of the advantages of using ABSM in rescue operations in open and dynamical environments were provided by Hernandez Encinas *et al*. (2007) and Abramson *et al*. (2008). The decision-making systems have generated high expectation during the last decade, becoming more complex and functional due to their great ability to hand large amounts of information for their specific analyses. ABMS represents a significant advance in the development of decision support systems, making these systems more flexible, reliable, and simple than any other standard central management systems. Thus, an agent is an autonomous, independent unit, capable of making decisions and interacting (communicating) with other agents or objects. In this sense, Maka *et al*. (2011) presented an agent-based model to solve some specific actions in a warehouse logistics process, giving a clear opinion on the advantages of ABMS over standard central management systems. Other examples of the advantages of ABMS in empowering the resource planning systems in a logistic process were shown in Cupek and Maka (2010) and di Lecce *et al*. (2010). Moreover, the field of artificial immune systems is a specific area of artificial intelligence, which permits to model and simplify the behavior of biological immune systems (Montealegre and Rammig, 2012). As ABMS can be used as a testbed for a better understanding of artificial immune systems and to find the solution to determined technical problems, Montealegre and Rammig (2012) presented an approach to explaining the operation of a method which is able to transfer the biological immune system principles to the field of artificial immune systems. To achieve this, the authors made a brief explanation of the behavior of artificial cells in biological systems, representing agents in a biological organism and demonstrating their functionality because such agents can model and simulate the operational performance of some cells within an entire ecosystem. The results demonstrate the good performance of the implementation in a cellular alarm management system. In accordance with Folcik *et al*. (2011), ABMS is a potential tool for facilitating the extrapolation of biological immune system principles into the field of artificial immune systems.

On the other hand, the use of the intelligent agent metaphor is one of the most studied approaches in the development of auction systems in virtual environments. This is because the agents are entities capable of assuming different behaviors determined by their role in a particular negotiation. However, according to Fard and Far (2012), the study and analysis of emergent behavior arose as an important challenge that must be taken into account before relying entirely on this technology within that scenario. Such an approach determines that emergent behavior can be eliminated from the modeling agent phase. Through this investigation, the methodology to achieve a reduction of 33% of a finite state machine synthesized in a realistic online auction system is detailed. Auction protocols that have been developed strengthen processes such as supplying chain management, distribution of multi-project schedule, e-manufacturing, and allocation of loads in transportation logistics. Such examples are becoming a trend among ordinary individuals, according to Wu (2001), Robu *et al*. (2011), and Adhau *et al.* (2012). For this reason, multi-agent approaches are suitable to be implemented in auction systems, simplifying a wide range of operations due to their social metaphor, such as selling, bidding, buying, and making all kinds of decisions around the auction processes, interacting with the other entities in the system in temporal encounters, called scenes. Although agent-based systems represent a wide range of benefits, modeling applications based on them involve endless specific design challenge. To present a proper solution for this problem, ABMS is dedicated to facilitate interaction and communication between agents. In fact, the artificial intelligence community has a strong belief that ABMS has an important place among the areas that comprise the agent field. For example, IEEE FIPA (Foundation for Intelligent Physical Agents) represents the efforts of various sectors such as government agencies, individual companies, research centers, and universities, whose aim is to establish a standard requirement for the design and development of the interaction between agents and agent-based systems. Specifically, the main objective of FIPA is to facilitate and ensure that agents can achieve high levels of interaction based on architecture, communication, and operation. Such efforts are a reflection of the great relevance that agent-based systems have taken over the last 20 years, looking for solutions to different types of processes in an efficient, safe, and effective way in open and dynamic scenarios.

3 Related work on traffic technology

Transportation systems are a crucial part in the social, economic, and political development of any city in the world. In fact, one parameter to enhance the quality of a determined country is to have an efficient and trustworthy transport system not only in urban traffic but also in road, air, and rail sectors. Thus, taking into consideration urban roads, one of the main aspects in the control and management of vehicular traffic is consideration of the level of service offered to users (i.e., vehicles and pedestrians). In fact, there are several methodological strategies to reduce traffic volume and minimize the generation of greenhouse gases caused by vehicles in the automotive sector. These strategies use mainly electronic systems handled by microcontrollers and microprocessors. Although they have evolved over time, they continue presenting several limitations to prevent modifications. Among all the variables that must be considered to develop a robust system for the control of traffic lights, the interpretation of the volume of vehicular traffic stands out as the most important issue because this information allows determining the timing of the signals of traffic lights. For example, Saeed *et al*. (2011) presented a fuzzy model that uses wireless sensors to detect conditions to avoid congestion, accidents, and some other traffic irregularities. The main contribution of this approach is to provide solutions to minimize the time during which vehicles are stopped in a particular road junction, especially using a specific scheme to give priority to emergency vehicles in common traffic situations. In the same way, based on radio frequency identification technology (RFID) it is possible to measure vehicular speed on the road using the Hall effect-based sensor, as presented in Pérez *et al*. (2010). To do this, some sensors were previously installed on the road to provide information to a fuzzy logic controller. According to the results, it is possible to both demonstrate that unexpected situations arise as natural complications of the road and ensure the integrity of the users in their travels. To minimize the travel delays caused by a wrong scheduling of the red lights at an intersection, Zade and Dandekar (2011) developed a new intelligent traffic signal controller. They implemented a neural-fuzzy system which is able to make successful decisions to select a proper green interval in response to the requirements and constraints of the traffic. To do this, the system uses information about the volume of the vehicles on the road to provide a better green interval in a typical four-way junction. Roozemond (2001) provided a reactive approach for urban intersection control. The approach can respond to environmental changes in a traffic scenario by adapting the green intervals according to a set of predefined rules. Despite the current contributions derived from the computational domain, the development on the field of simulated test environments to control and optimize urban arterials is another interesting and promising area for further study. Nowadays, there are computational tools that offer the opportunity of implementing and testing approaches to corroborate their ideas. Nonetheless, these tools are not functional for all aims. Thus, some researchers tend to develop their own tools while generating their methodological proposals. For instance, Huang *et al*. (2012) developed and reviewed a reservation-based approach for intersection control. They referred to the development of a novel simulator to evaluate the behavior of vehicles in interconnected intersections. The system developed includes a microscopic traffic analyzer which can represent the behavior of the vehicles and measure the greenhouse emissions. Some experiments were carried out using the developed simulator to compare the service level of the road and environmental benefits of the introduced approach against those of traditional control methods. Methods provided by Hernandez *et al*. (2002), Garcia-Serrano *et al*. (2003), Zhang *et al*. (2004), Chen RS *et al*. (2005), Liu *et al*. (2005), van Katwijk *et al*. (2005), Wang (2005; 2008), and Chen B *et al*. (2006) are other examples of the aforementioned actions (Table 1). Derived from the relevance of studying specifically the domain of traffic systems in open, complex, and

Table 1 Platforms of traffic control and management

Reference	Key aspect
Chen *et al*. (2005)	An adaptive and cooperative traffic light agent model for decentralized traffic signal control
Chen *et al*. (2006)	FIPA standard; hybrid control architecture
Garcia-Serrano *et al*. (2003)	FIPA standard, to design traffic agent city for knowledge-based recommendation
Hernandez *et al*. (2002)	Study and comparison of centralized and decentralized agent-based architectures for intelligent traffic management in urban networks
van Katwijk *et al*. (2005)	A testbed to allow designers of MAS to experiment with different strategies and examine the applicability of developed systems
Liu *et al*. (2005)	A multiagent simulation framework to evaluate the usability of the demand bus system
Wang (2005; 2008)	Description of both hardware and system implementation, as well as its field deployment in real-world urban traffic control integrating mobile agent concept
Zhang *et al*. (2004)	MAS architecture for distributed traffic data process and management

distributed domains, Chen and Cheng (2010) gave a general review of several approaches in the literature. In particular, they presented a study oriented to agent-based traffic applications which can be classified into five ranges: (1) agent-based traffic control and management system architecture and platforms, (2) agent-based systems for roadway transportation, (3) agent-based systems for air-traffic control and management, (4) agent-based systems for railway transportation, and (5) multi-agent traffic modeling and simulation. However, software agents and artificial intelligence techniques in urban traffic systems have arisen as a proper solution in the last decade to provide high levels of efficiency in transport infrastructures. Despite these efforts, the design, development, and implementation of agent technology in traffic control systems are still immature and need further study.

Limitations of previous studies on intelligent transportation systems (ITS) include:

1. Early studies on ITS attempt to assess the level of service on the road to reduce the time that cars spend needlessly at a red light. Other interesting phenomena that should be studied are those related to acceleration and deceleration, unnecessary fuel consumption, and auto parts wear, when vehicles should stop multiple times due to poor planning of the pre-programmed traffic light signals. For this, environmental advantages of ITS must be more widely studied in a near future.

2. Studies devoted to ITS research are not able to use information about decisions taken previously when the junctions must be adjusted to offer a better level of mobility under overloaded traffic volume.

3. Other models implemented to manage the control of traffic-light signals cannot use a communication protocol in the phase of synchronization of the light time in order to reach a successful interaction between intersections.

4. The current simulators in the literature cannot work in real time and they are also not designed to auto-synchronize the time of the traffic signal lights while an experiment is being performed.

4 Traffic signal control

Long lines of vehicles, wide ranges of stop-times in intersections and environmental emissions are only some of the aspects that traffic control is looking forward to eliminating. The transportation community has a great interest in bringing forth techniques to represent, model, and assess traffic situations in interconnected transport networks (Table 1). Fig. 1 depicts the general scheme of the methodology proposed in this paper, which consists of five modules: (1) traffic simulator module, which uses a novel traffic simulator to simulate the traffic system and embeds two modules created for the simulator vehicle generator and intersection configurator, respectively; (2) infrastructure module, which contains all the operators envisioned in the interconnected intersections; (3) communication module, which serves as a protocol of communication to inform other operators and to make commitments among them (see Section 5.1); (4) decision module, which endows operators with reasoning skills in order to find some alternatives to deal with any particular situation in a

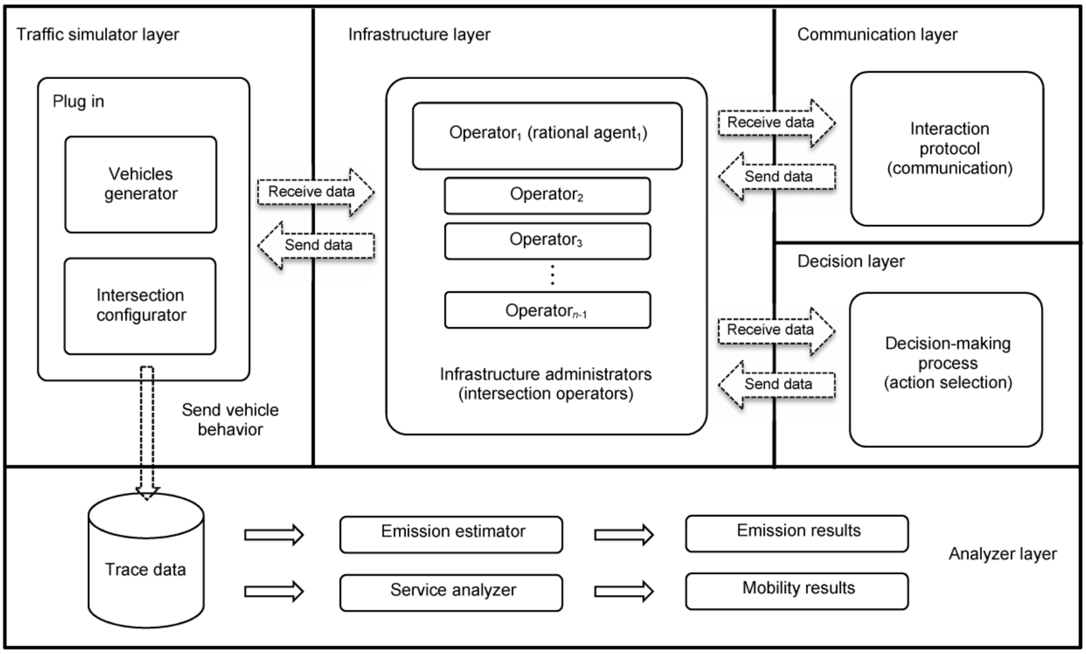

Fig. 1 General scheme of the proposed architecture

determined lane of an intersection (see Section 5.2); and (5) analyzer module, which performs both mobility and environmental analyses based on the time at which the vehicle arrives and departs within some lane of any intersection. To follow, the performances of all the five modules are described, with the decision module being emphasized.

4.1 Traffic simulator module

To start, the traffic simulation module is responsible for generating the simulation volume of cars, representing the arrival and departure of the car at a certain line of the junction and establishing the movements and the cycles of the lights at every intersection. The literature on traffic simulators presents multiple options to study and evaluate the behavior of traffic lights in order to provide a better level of vehicular mobility in a network of multiple intersections. In particular, the traffic simulator outlines the way vehicles are injected in each lane of a particular intersection. Vehicles are injected according to the data obtained by studying the behavior of the users in a group of selected real intersections in Madero and Tampico Cities (Mexico). For each lane of an intersection, there exists a generator e_i of vehicles such as

$$\forall \text{lane}_i \in I_\infty,\ \exists e_i = \sum \left[\text{abs}\left(\frac{r_i \mu_i}{\sigma_i} \right) \right]_{t_{n-1}},$$

where r is a variable about the observed frequency of the vehicles, and μ and σ are constant values obtained by a statistic analysis of the data and both are updated automatically by the module throughout the simulation. The number of vehicles injected is controlled as follows:

$$\Phi(e \in \text{lane}_i) = \sum_{e_i=1}^{\infty-1} e_i,\ \Phi(e \in I_\infty) = \sum_{\text{lane}_i=1}^{m-1} e_i \sum_{e_i=1}^{\infty-1} e_i.$$

In addition, the type of vehicles is controlled as a vector $\boldsymbol{\Theta}(e\in\text{lane}_i)=[\theta_1\vee\theta_2\vee\ldots\vee\theta_{c-1}]$. For the proposed rational control of intersections, the configurator of the intersections is used to indicate the movements allowed in each lane and to set the sequence and the time of the lights in each intersection. Such a configurator offers the users the opportunity to indicate the initial data about the frequency of the vehicle arrival and the initial length of the cycle. In this sense, the system interacts with the traffic analyst using the traffic simulator module.

4.2 Infrastructure module

In this module, the approach comprises a number of intersection operators A according to the amount of intersections I in domain D, where each operator $O \in A=\{o_1, o_2, \ldots, o_{m-1}\}$ is responsible for controlling the duration of each traffic light in a determined intersection $I \in D=\{i_1, i_2, \ldots, i_{n-1}\}$ across the network of interconnected intersections. After receiving information from the traffic simulator module, each rational agent is assigned to a particular intersection; for this, each agent is aware of the length of the cycle and the vehicle arrivals. Besides, an intersection is composed of lanes $l_i \in I_j$ (i=1, 2, …, p−1), where for each lane the operator must control the sequence and the scheduling of a traffic light. All this data allows agents to create a case C_n of a particular situation in each lane so as to define a strategy to improve the level of service in each lane of the intersection. Each case is constructed using the data of the studied lane as follows:

Case$_n$
V_L=volume of vehicles.
t_{gi}=length of green light for that lane.
D=distance (quantity) between the first and last vehicles in the longest rail.
n=number of rails in each lane.

4.3 Communication module

One of the main benefits of this approach is that the previous module is based on the agent metaphor. For this, the communication module can be easily replaced. Modifying the communication module only, different communication scenarios can be simulated. With the communication process being integrated among operators, an adaptation of the KQML protocol is proposed in the module, which will be described in Section 5.1.

4.4 Decision module

A decision is the process through which an operator of any lane can consider the information provided by the traffic simulator module to decide what must be done to improve the mobility of the vehicles in a specific lane and to reduce emissions in a representative way. To achieve this target, some algorithms with the ability to mimick human intelligence are used in this module. In this sense, these technologies permit the implementation of real-life rules similar to those people usually resort to. Based on previous and successful decisions, an operator can offer a better time to each green light. Such effects are reached by using the case-based reasoning methodology, which will be described in Section 5.2.

4.5 Analyzer module

This module is the administrator of calculating the service level and the environmental indicator of each intersection in the whole network. By this module the generation of environmental emissions can be measured similar to the comprehensive modal emission model (CMEM), which is a microscopic emission model that predicts tailpipe emissions and fuel consumption based on a second-per-second physical power-demand modeling approach (Scora and Barth, 2006). In this study, CMEM is used only as a motivational model. Using the model included in the module, a simple experiment is run to corroborate the level of feasibility and accuracy of the model to calculate the effect of fuel consumption when vehicles are stopped at a red light. Fig. 2 compares the fuel consumption of a four-way intersection with the real data previously obtained. The sum of the pollutants in the real scenario is close to that of the proposed model. For example, during the period from 0 to 30 s, the two curves are almost overlapping. This simple experiment clearly demonstrates the effectiveness and accuracy of the generated model.

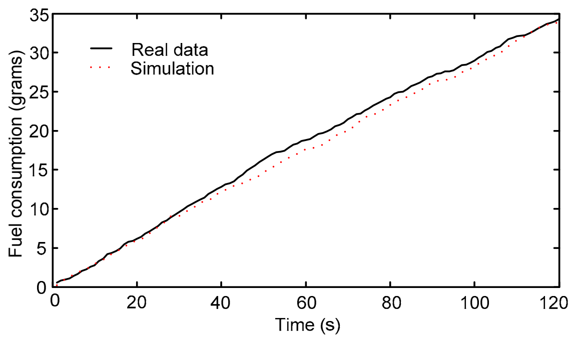

Fig. 2 Comparison of the fuel consumption of a four-way intersection with the real data previously obtained

5 Optimizing traffic flow

Optimizing the traffic flow in a particular network of interconnected intersections requires several point-of-views, i.e., software engineering, intelligent systems, and optimization structures. Prior to this, an integrated simulator was developed in Matlab to plug into each one of the presented modules. Fig. 3 shows the main screen of the developed system. The simulator that outlines intersections with different characteristics can simulate the injection of vehicles into each lane. It is possible to set three labeled functions: CBR, cars simulation, and data acquisition. In particular, if the CBR option is not selected, the system uses a pre-programming scheduled length for each traffic light provided by the user. The configuration also allows fixing the time of the experiment and gives the clock-time of the simulation. A simulation data section allows the appreciation of the traffic light cycle operation and the volume of vehicles in each traffic signal.

5.1 Interaction protocol

KQML language is a facilitator for coordinating the interactions of multiple intelligent entities to support knowledge sharing. Operators must interact with others both to argue a possible transfer or assignment of green light time and to inform about the actions performed by the operator. For example, in Fig. 4, Operator$_1$ sends several sentences to the communication module. The communication module translates and reports the information sent by each operator to the remaining operators in the network. The module interprets what the operator wants to inform other operators and publishes the data.

Fig. 3 Integrated simulator

The basic structure of each message is presented in Fig. 5.

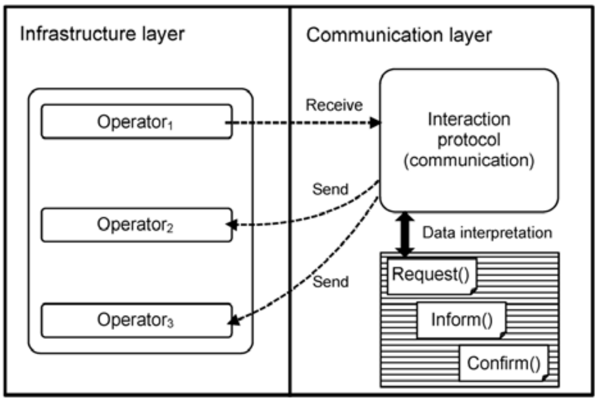

Fig. 4 Communicative process

5.2 Decision-making process

The new decision process proposed in this study differs from those in previous studies (Borne *et al.*, 2003; Balbo and Pinson, 2005; Ossowski *et al.*, 2005) in that the decision-making process requires updated operators to know the constraints and requirements in their assigned infrastructure and to modify the length of the green light in each specific lane. Operators use this module to mimic the behavior of a transit officer taking into account the variables of the case mentioned in Section 4.2.

(performative_request…		(performative_confirm…		(performative_inform…	
:sender	Operator$_n$	:sender	Operator$_m$	:sender	Operator$_m$
:receiver	All operators (A)	:receiver	Operator$_n$	:receiver	Operator$_n$
:content	required_green_time_to_line$_i$	:content	assigned_time	:content	declined_time
:ontology	Require(O_n, A, line, 9 s)	:ontology	Confirm(O_m, O_n, 1, 4 s)	:ontology	Inform(O_m, O_n, 0 s)
…)		…)		…)	

Fig. 5 Structure of the messages

$Case_n$
V_L=volume of vehicles.
t_{gi}=length of green light for that lane.
D=distance (quantity) between the first and last vehicles in the longest rail.
n=number of rails in each lane.

In a given case, the module performs an adaptation of the cases-based reasoning methodology (de Mantaras *et al.*, 1997) aiming to provide operators with adaptive actions implementing a strategy to improve the green time interval efficiency.

Retrieve—An operator must review the volume of vehicles injected by the traffic simulator module before the green light turns on. Using the quantity of vehicles Φ and the green time interval t_{gi}, the operator looks inside the cases-base to extract the most similar cases using the Tanimoto index (Berkhin, 2006), where the variable ranges are $\{-5 \le V_L \le +5\}$ and $\{-2\text{ s} \le t_{gi} \le +2\text{ s}\}$. The operator retrieves n cases and computes the average green time interval. Such a process is used to obtain the possible length of green light offering a proper solution for the presented conditions of the lane. For this, the selection of a suitable case (or cases) from the cases-base is another interesting question. Fig. 6 confronts the sensitivity of selecting an effective case to deal with any given situation versus the specificity of taking a wrong case. For the proposal of this approach, this analysis permits to argue that the selected method for the retrieval phase (Section 5.2) is appropriate and trustworthy for the intentions of this work.

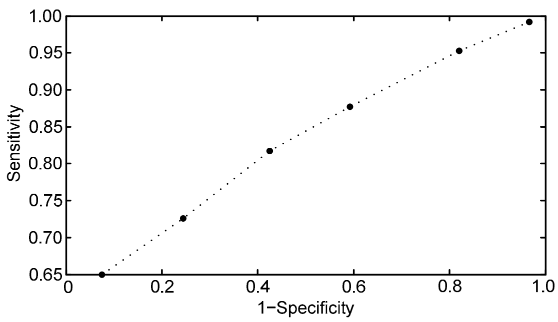

Fig. 6 Sensitivity of selecting a suitable action for a situation

Reuse—A new solution is generated from the retrieved cases according to the problem conditions. At this stage the recommended length for the green interval is adjusted according to a suitable level of service and the performance of the entire intersection.

Revise—The operator must evaluate the behavior of the implemented action measuring the volume of remaining vehicles V_Q in the studied lane. To do this, the operator uses Eq. (1):

$$V_Q = \left(V_L - \frac{n t_{gi}}{D} \right)_{t_0}, \quad V_Q = \begin{cases} 0, & V_Q < 0, \\ V_Q, & V_Q \ge 0. \end{cases} \tag{1}$$

Retain—After revision, if the operator considers that this action achieves at least a performance of 51% (which means that 51% of the vehicles have already left the lane), the studied problem and the proposed solution have to be indexed in the cases-base for use in future interactions of the module.

6 Experiments

Experiments have been implemented to simulate and assess the likely mobility and environmental benefits of the intelligent control (IC) concept compared to the traditional control (TC) approach. Two test cases are considered: (1) a connection between two four-way intersections and (2) a network of two different types of intersections. The simulations are performed at four demand levels 50%, 100%, 150%, and 200% according to a usual arrival of vehicles per second using the vehicles generator presented in Section 4.1. For each case, the results are presented by showing the average of the 10000 experiments covered in only one hour. The emissions are calculated based on information obtained from the INEGI (www.inegi.org.mx). From the data obtained in the performed simulations, some preliminary results have been obtained to assess the usefulness of the methodology introduced in this paper.

6.1 Test case 1

A two-interconnected four-way junction is simulated in the developed system with traditional preprogramming control (Fig. 7) and the incoming vehicle data is provided in Table 2.

The performances are compared to demonstrate the benefits of the traffic lights based on IC over TC. Fig. 8 shows that compared to the TC approach, IC

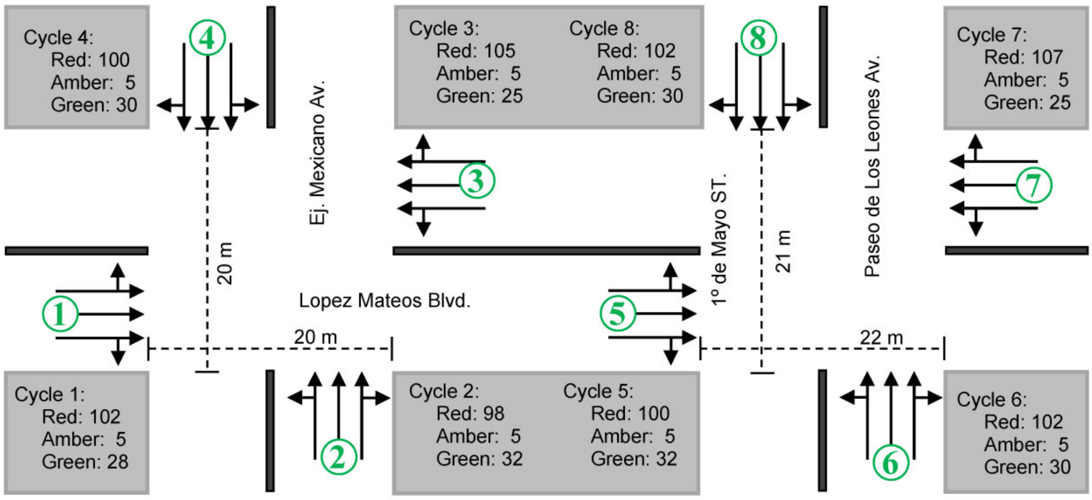

Fig. 7 General scheme of case 1

Table 2 Data observed from the real study count

Demand level	r		μ		σ	
	Int_1	Int_2	Int_1	Int_2	Int_1	Int_2
50%	[0–1]	[0–1]	2.5	2.6	1.8	1.7
100%	[0–3]	[0–2]				
150%	[1–4]	[1–3]				
200%	[2–4]	[2–4]				

Int_1: intersection 1; Int_2: intersection 2

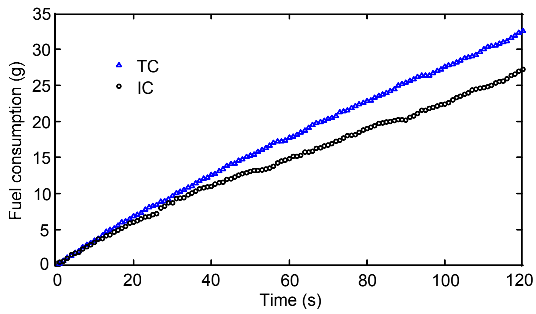

Fig. 8 Fuel consumption in a determined intersection

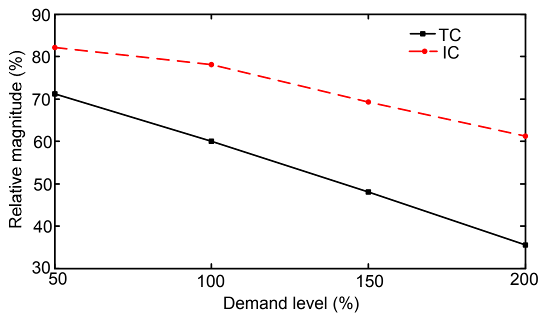

Fig. 9 Average of the served vehicles in test case 1

reduces the fuel consumption by almost 16%. Fig. 9 shows the mobility performances of IC using the CBR filter and TC. Specifically, such a comparison is made between the number of vehicles that arrive and the total number of vehicles dispatched through the intersection at a 100% demand level. Focusing on the average service increase (Fig. 9), the proposed methodology appears to be capable of substantially improving the service level of a particular intersection. For instance, the performance of the service using IC is better than TC by around 23% at a demand level of 100%. Moreover, the environmental evaluation focuses on the reductions in fuel consumption, as well as the reduction of the following four pollutants: (1) hydrocarbons HC, (2) carbon monoxide CO, (3) nitrogen oxides NO_X, and (4) carbon dioxide CO_2 (Fig. 10).

Fig. 10a compares the fuel consumption (in g/s, generated by stopped cars while the red light is on) and the emission level of three of the pollutants (also in g/s) under IC and TC for different demand levels. Fig. 10b presents the remaining pollutant. For example, at the demand level of 100% (Fig. 10b), the magnitude of CO_2 emission under the control of rational operators shows a better performance than the one controlled by traditional methods, by around 35%. In particular, the implementation of such operators based on past decisions and by coordinating the length of the cycles, appears to have significantly reduced the emission. As the demand level has increased all the emissions and fuel consumptions, IC manages to reduce or maintain both the emissions and fuel consumptions. In addition, Fig. 11 compares traffic velocity against traffic volume. This comparison identifies the advantages of the proposed methodology over the traditional approach in improving vehicular mobility under different types of volume demand. The complete analysis results are summarized in Table 3.

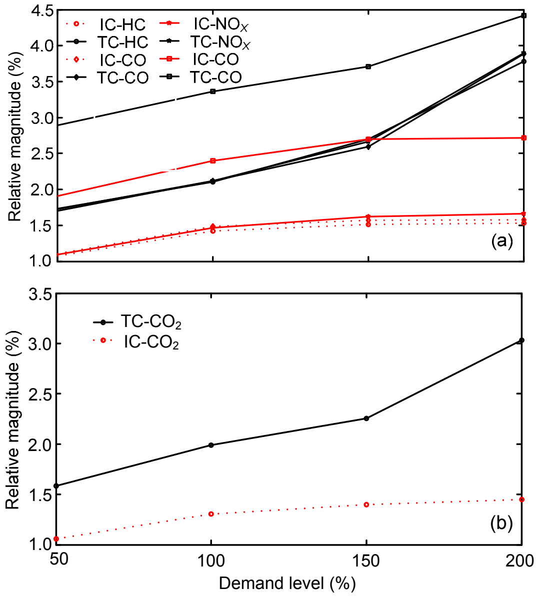

Fig. 10 Comparison of experimental results
(a) HC, CO, NOx emissions and fuel consumption; (b) CO_2 emissions

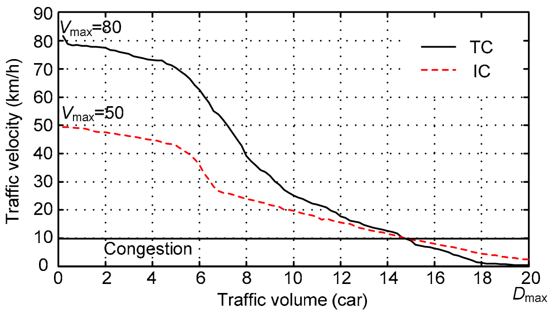

Fig. 11 Traffic velocity versus traffic volume

Table 3 Emission and fuel consumption (Case 1)

	Demand level	Relative magnitude (%) IC	Relative magnitude (%) TC	Improvement rate* (%)
HC	50%	1.0760	1.7340	37.95
	100%	1.4230	2.1070	32.46
	150%	1.5120	2.6990	43.98
	200%	1.5280	3.7800	59.58
CO	50%	1.1080	1.6980	34.75
	100%	1.4860	2.1210	29.94
	150%	1.5690	2.5930	39.49
	200%	1.5740	3.8870	59.51
CO_2	50%	1.0572	1.5864	33.35
	100%	1.3055	1.9887	34.35
	150%	1.3971	2.2557	38.06
	200%	1.4484	3.0330	52.24
NO_X	50%	1.0920	1.7250	36.70
	100%	1.4630	2.1190	30.96
	150%	1.6240	2.6640	39.04
	200%	1.6620	3.8950	57.33
Fuel	50%	1.9090	2.8930	34.01
	100%	2.3980	3.3630	28.69
	150%	2.6990	3.7080	27.21
	200%	2.7200	4.4200	38.46

IC: intelligent control; TC: traditional control. * IC over TC

6.2 Test case 2

The second test (Fig. 12) involves data of a real-world intersection, taking into account one of the most important roads in Tampico City, MX (Hidalgo Ave) and three different streets (Rotaria St., Agua-Dulce St., and Francita St.). The data used in these experiments has been obtained in real traffic studies dating from Oct. 2011 to Mar. 2012 (Table 4). The results obtained are compared to emphasize the advantages of traffic control based on rational agents over the pre-programming traditional control used in the synchronization phase of the studied intersection. To evaluate the decision-making process of the IC approach proposed in this work, Fig. 13 depicts how IC reaches a suitable behavior after 100 decisions along 1000 trials. This effect emphasizes the ability of rational operators to make sure decisions with a better performance when they resort to information from previous situations that have been dealt with successfully. The performance does not improve significantly beyond 100 trials. This number of trials is therefore used initially to confirm the decision performance. In particular, there is an improvement rate of around 21% reached by IC over TC. Such analysis discloses that mobility problems can be avoided if the proposed approach is implemented for traffic light signals.

In addition, Fig. 14 plots the mobility level confronting the volume of incoming vehicles against their departure. To demonstrate high levels in the mobility aspects, the results reported show that IC achieves a better performance than TC, by around 18% under a demand level of 100%. Note that the performance does not improve significantly when the demand level is more than 100%.

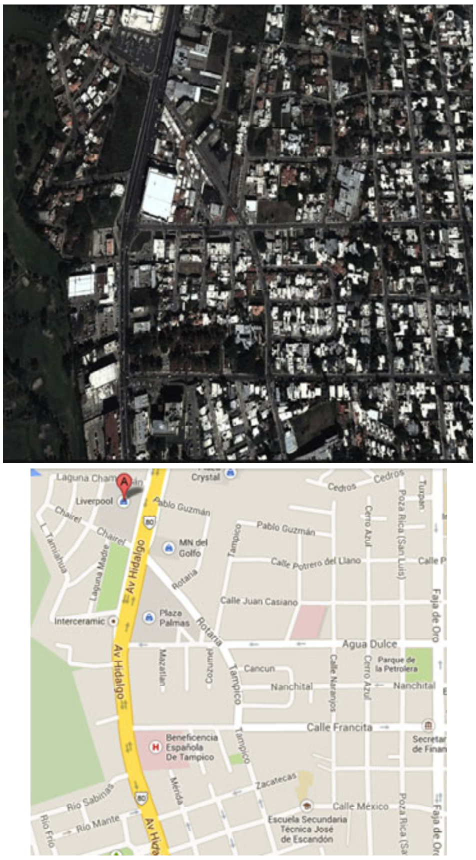

Fig. 12 Snapshot of a real scenario: (a) Google Earth; (b) Google maps

Table 4 Data observed from the real study count at four demand levels

Data	Intersection	Value			
		50%	100%	150%	200%
r	1	[0–1]	[0–2]	[1–3]	[2–4]
	2	[0–2]	[0–3]	[1–3]	[2–4]
	3	[0–2]	[0–3]	[1–3]	[2–4]
μ	1	2.3			
	2	2.5			
	3	2.1			
σ	1	1.7			
	2	1.1			
	3	1.1			

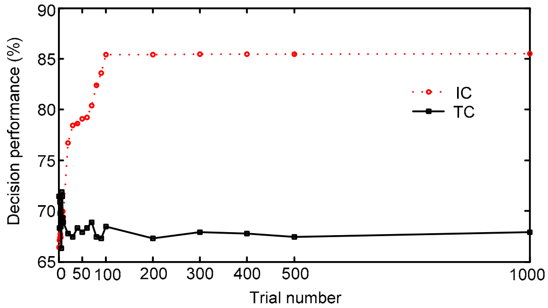

Fig. 13 Comparison of decision performance between IC and TC at different numbers of trials

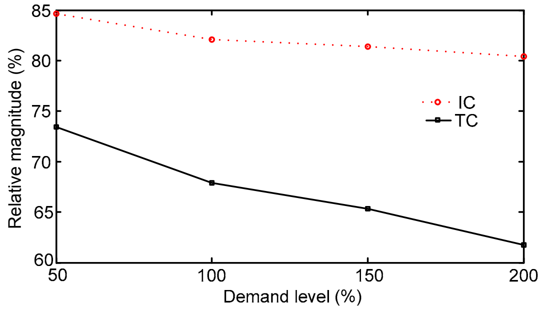

Fig. 14 Average of the served vehicles in test case 2

Fig. 15 shows the average achieved in the reduction of CO_2 volume while vehicles are stopped. For example, the CO_2 magnitude emission when intelligent agents control the traffic lights achieves a considerable improvement of around 45% in comparison with the performance achieved by traditional control in real world infrastructure. Fig. 16 compares traffic velocity against traffic volume. This comparison identifies the advantages of the proposed methodology over the traditional approach in improving vehicular mobility under different types of volume demand. The complete analysis results are summarized in Table 5.

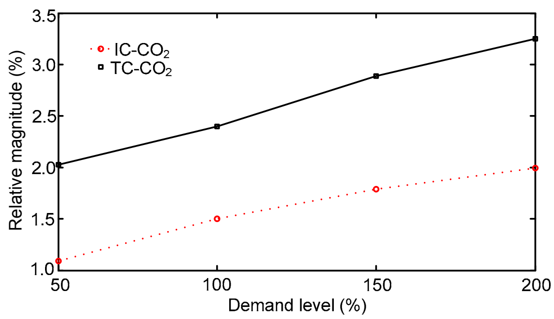

Fig. 15 Relative magnitude of CO_2

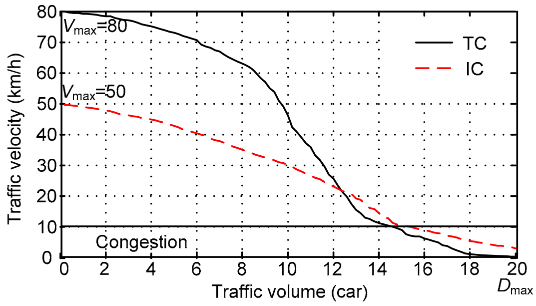

Fig. 16 Traffic velocity versus traffic volume

Table 5 Emissions and fuel consumption (Case 2)

	Demand level	Relative magnitude (%) IC	Relative magnitude (%) TC	Improvement rate* (%)
HC	50%	1.1005	1.6849	34.68
	100%	1.4230	2.1070	32.46
	150%	1.5120	2.6990	43.97
	200%	1.5280	3.7800	59.57
CO	50%	1.0975	1.7001	35.44
	100%	1.4860	2.1210	29.93
	150%	1.5690	2.5930	39.49
	200%	1.5740	3.8870	59.50
CO_2	50%	1.0912	2.0264	46.15
	100%	1.4995	2.3984	37.47
	150%	1.7891	2.8897	38.08
	200%	1.9919	3.2530	38.76
NO_X	50%	1.0889	1.7319	37.12
	100%	1.4630	2.1190	30.95
	150%	1.6240	2.6640	39.03
	200%	1.6620	3.8950	57.32
Fuel	50%	1.8899	2.9002	34.83
	100%	2.3980	3.3630	28.69
	150%	2.6990	3.7080	27.21
	200%	2.7200	4.4200	38.46

IC: intelligent control; TC: traditional control. * IC over TC

7 Conclusions and future work

Road traffic congestion is one of the main causes of low productivity and the decrease in modern city standards. In this sense, some recent trends in artificial intelligence suggest that in the near future, intelligent agents will improve some road challenges. Based on a ubiquitous computing paradigm, the control of the traffic based on intelligent agents offers an ideal path to operate the vitalities using the Internet or other ad-hoc interconnections based on real world time information. The flexibility of the rational agents allows for making decisions in similar ways to a human being. For this reason, we introduce a novel methodology to manage traditional traffic control using rational agents. Specifically, agents are in charge of ensuring that at least 51% of vehicles are dispatched during a green light interval. To do this, the agents use an adaptation of the CBR methodology, which is also similar to that of a police officer handling the traffic flow at a typical junction. This human-based process allows agents to be capable of evaluating past decisions from a database built over time. In this light, the work develops an integrated simulator to design and evaluate the requirements and constraints of an intersection. The simulator permits users to configure different aspects of a determined intersection in order to provide results that disclose the behavior of the traffic flow and other relevant information such as pollutant emission and fuel consumption. The simulator also reports the changes of the lights in each traffic signal throughout the experiments. Finally, the studies performed in the integrated simulator are used to evaluate not only the advantages in the offered service but also the environmental influence of this promising strategy. Consequently, the volume of attended vehicles and the fuel consumption as well as greenhouse emissions under traffic light control based on intelligent agents, are compared to those under traditional signal control. Different configurations have been considered in two experiments, one involving two-connected isolated intersections and the other considering multiple intersected roads. From the results obtained, it is possible to argue that the proposed approach achieves significant benefits in vehicular mobility, in terms of congestions by increasing the traffic capacity of any intersection. However, for future investigation, issues such as acceleration and des-acceleration, collision avoidance and vehicles with different velocities, must be included in the simulator by offering a set of more realistic situations in the virtual instrument proposed here.

This work has focused on assessment of the mobility and environmental benefits in order to study the service level and the environmental effects in a determined intersection. Future research should include other relevant aspects of the real world such as pedestrian, service vehicles (ambulance, police, etc.), and emergent problems (crashes, broken cars, etc.).

Intelligent traffic lights using sophisticated computational algorithms are a promising approach to autonomous intersection control. In spite of this, there are some limitations about the scope of this work. For example, the adaptation of other automatic learning techniques could be required to evaluate the effectiveness of using rational agents to optimize urban traffic control. The simulator should include more variables such as humidity, temperature, barometric pressure, and other relevant aspects of the world, in order to make a more realistic analysis of the environmental benefits of this approach. In addition, the presented work must assess whether the proposed approach is adaptable to any type of junction with the aim of ensuring a high level of vehicular mobility. To conclude, intelligent and communicative agents are employed to control traditional pre-programming traffic lights ensuring autonomy without losing security and effectiveness in vehicular flow optimization using CBR. Therefore, this paper makes two main contributions:

1. A novel and preliminary methodology is proposed to optimize traffic flow using intelligent agents. This paper reports a good and feasible structure to use previous decisions to guarantee that most vehicles are served when the green light is on.

2. A computational tool is an instrument to simulate the behavior of junctions to evaluate vehicular mobility, fuel consumption, and greenhouse emission. This paper argues that there is a need to build new systems to satisfy the requirements of the traffic experts in a more friendly but reliable and effective way. The utility and feasibility of the proposal have been demonstrated.

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