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A Novel Approach to Modular Control of Highway and Arterial Networks using Petri Nets Modeling

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ABSTRACT

In this paper, integrated control of highways and intersections is investigated. A modular Petri-Net-based framework is implemented to model the traffic flow of highway and arterial traffic network systems. In this framework, arterial intersection traffic lights are modeled by Timed Petri Nets (TPN). The timing of traffic lights and variable speed limits on the highway is managed to be optimized using an intelligent algorithm. This algorithm provides a trade-off between the length of the queue of vehicles on the highway and the entrance ramp and the length of the queue at the intersection after each time cycle. The performance of the optimized traffic controller and the fixed control were compared. The simulation results verify that the use of optimization methods to manage the timing of traffic lights in intersections and speed limitation in highways can considerably improve traffic flow in special conditions such as rainy weather and accidents. Additionally, this method can considerably enhance traffic flow in normal hours, while in rush hours and midnight, such improvement is negligible.

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1. INTRODUCTION

Nowadays, the urban transportation sector is one of the major emitters of greenhouse gases. The number of vehicles traveling in urban areas is increasing, especially in metropolitan areas, due to the rapid growth of urban areas. This incremental growth in the number of on-road vehicles has led to an increasing number of undesirable drawbacks such as heavy traffic, air and noise pollution, road congestion, and waste of citizens' useful time which will indeed lead to a higher citizen dissatisfaction rate. A sign of these drawbacks may be seen in the growing number of research in this field [1].

Traffic control is considered to be a very beneficial and cost-effective approach to overcome the aforementioned problems in comparison to infrastructural development. Designing a solution for improved traffic control performance is conducted through two different approaches in the literature: Highway Networks Control and Arterial Control, with the latter tending to manage the control of intersections and urban arteries. The highway network control approach imposes restrictions on highway entrances. Speed limits on the upstream will reduce congestion and facilitate traffic [2]. Furthermore, much research has been conducted to investigate the effectiveness of the input control method. The performance of these methods is evaluated using the comparison with local scheduling strategies [3]. These experiments demonstrate the superiority of this approach over local and no-control strategies. Different input control strategies have been implemented and tested in Paris and Amsterdam [4]. Taheri et al. [5] used queueing system analysis to provide an analytical method for calculating the fixed-time control system's average waiting time at a single isolated intersection.

Furthermore, the same methodology was applied to control the input as well as the speed limit simultaneously for one ramp and two-speed control panels. The coordinated feedback control of the input and the control of the mainstream traffic flow on the highways was applied using speed limitations [6]. Furthermore, a Resilliance Control for multi-lane highways in the presence of vehicle counting systems and prediction

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engine has been proposed by Mohammadi et al. [7].

In the arterial control approach, the most common way to regulate and manage urban traffic is to control the timing signal of traffic lights. Regarding work introduced by Fu and Chen [8], these functions are categorized into two groups; Fixed Time Control Systems and Traffic Responsive Control Systems. In the first category, pre-scheduled timing scenarios are executed using the offline optimization method. In the second category, the traffic control strategy is executed using optimized timing scenarios obtained from stimulated signals from traffic sensors and an online optimization method.

The origin-destination (O-D) pairs that colored Petri networks consume were analyzed by Fu and Chen [8], along with the latency that could be computed between Petri net nodes. Each node holds data about network subregional congestion, and colored tokens represent automobiles that move through the graph over time, following an O-D pair.

In addition to these studies, the utilization of Petri nets (PNs) in modeling, performance analysis, and control of traffic systems has been used for several years [9]. Additionally, a timed Petri net is utilized to model the timing maps of traffic lights controlling the intersections [5], implemented deterministic-timed PN (DTPN) for a microscopic model of a signalized traffic urban area, including signalized intersections and roads. This paper presents a Traffic Responsive Control System based on the colored timed Petri net (CTPN) model and Macroscopic models of traffic flow. Microscopic models are very detailed, and consequently, the computational effort can be exceptionally high when modeling large road networks. On the other hand, macroscopic models are less computationally intensive and can be used to model large road networks with an acceptable computational load. However, this computational advantage is balanced by their inability to capture some specific traffic phenomena related to the behavior of individual drivers. CTPN [3, 9, 10] describes traffic more finely: vehicles are individually shown by considering the interactions between them. By contrast, the macroscopic models represent the traffic flow with general variables such as the flow rate, flow density, and average flow speed. In the past literature, modeling is either considered microscopically for intersections or macroscopically for highways. At the same time, both models have been considered in the model proposed in this paper. The proposed control system aims to control the timing of traffic lights to reduce traffic jams in a certain part of the city. This urban area consists of three intersections and a highway [11], traffic light schemes with two extra traffic signals were defined using a Petri nets method. A warning on a particular road will be announced on one, and a road closure will be announced on the other. They made assumptions about the start and end dates of the strategy's operational period.

With respect to Fu et al. [12] Multi-Regional MFD Systems with Boundary Queues have been designed using Colored Petri Nets for both Perimeter Control and Route Guidance. The intersections and road segments that separate each pair of adjacent subregions are modeled as a buffer zone in this Accumulation-based traffic model using Petri Nets, which is introduced here as a reference for perimeter control. The proposed control framework incorporates both perimeter control and route guiding, taking into account the waiting cars in the buffer zones.

A large number of studies have been carried out to develop different signal timing plans, which are mainly classified into three classifications fixed-timed, predictive control strategies, and traffic responsive [13]. The first one is widely adopted in most current urban traffic systems due to their inexpensive and easy implementation. However, its disadvantage is that the time plan is fixed even in abnormal conditions. The second one is based on an optimization control strategy that can predict the future traffic behavior of the network based on traffic-forecasting models. The third one is based on those measured current traffic states and has been effectively used in many cities around the world. In this paper, the signal timing plan of the intersections and speed limitation in highways are determined so that traffic congestion is minimized. In other words, we deal with an optimization problem aiming to maximize the traffic flow using a signal timing plan of the intersections and speed limitation in different sections of the highway. The superiority of this method in comparison with other studies is modular traffic network modeling. In other words, any possible structure of the traffic network containing several intersections and highways can be created using this modular system. In contrast, other studies just considered either intersections or highways while, in a modular framework, the dimension of the traffic network becomes huge, and therefore, the computational cost is heavy. Additionally, in this modular framework, the performance of the proposed control system can be evaluated under various types of abnormal conditions such as rainy weather, accident occurrence, temporary obstruction, and any stochastic fluctuation in demand.

Bargegol et al. [13], investigated the correlation between speed, density, and flow in various conditions by analyzing the conduct of pedestrians while crossing both within and outside of crosswalks, and considering the duration of crossing during both pedestrian green and red times. The study employs linear and non-linear regression analysis to obtain these findings. In the work that follows, Petri nets and evolutionary algorithms are combined. Srivastava and Sahana [14] attempted to optimize waiting times in a city network model using this technique. In the study, the authors employed a hybrid technique that included ACO, GA, and the Stackelberg competition model to reduce the average waiting time in the tested network by 4% more than they could have with an evolutionary algorithm that had found the best solution on its own. Luo et al. [15] investigated the utilization of CTM for the purpose of devising control tactics to address traffic congestion resulting from dispersion accidents. Additionally, the effectiveness of said strategies is evaluated. The utilization of deep learning methodology for the identification of traffic congestion was suggested by Perez-Murueta and colleagues in 2019. The utilization of deep learning and k-shortest path algorithm was suggested by the authors for the purpose of identifying traffic congestion [16].

The paper is organized as follows: The next section describes the urban area in a modular representation. Section III represents the formulation of the problem as an optimization problem. In section IV, various traffic scenarios used to evaluate the proposed control system are described, and simulation results are presented under different scenarios. The conclusion of the paper is presented in the last section.

2. MODULAR MODELING OF THE HIGHWAY, INTERSECTIONS AND LINKS

Traffic flow can be modeled as a hybrid system characterized by continuous and discrete behaviors. The continuous behaviors of traffic flow use continuous Petri nets with variable speed (VCPN) to model and analyze the highways from a macroscopic point of view, whereas in discrete ones, colored timed Petri nets (TPN) are used to describe traffic flow in intersections from a microscopic point of view. VCPN [17, 18] describes traffic flow by global variables such as the flow rate, the flow density, and the average flow velocity. In contrast, TPN focuses on the individual vehicle's behaviors in the streets .

As mentioned before, VCPN can model the traffic flow on the highway, and TPN can be used to represent how the vehicles move in the intersections; therefore, in this section, the modular modeling of the highway and intersections using VCPN and TPN are presented, respectively.

2. 1. Highways Modelling by VCPNs Continuous Petri Nets with Variable Speed (VCPN) are proven to be suitable to model traffic flow with modular spatial discretization. VCPN model for a segment of highway is shown in Figure 1.

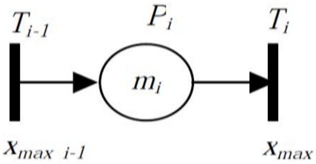


Figure 1. VCPN model for a segment of highway

Each place P_i corresponds to the segment $[x_{i-1}, x_i]$ whose length can be variable. The transition T_i represents the stream from one segment to another. The marking $m_i(t)$ of the place P_i stands for the number of vehicles $n_i(t)$ in the named segment. The transition firing speed $x_i(t)$ stands for the flow rate $q_i(t)$. C_i and Δ_i denote the capacity and length of segment i respectively. $v_{free\,i}$ and α_i are maximum velocity and firing rate of each segment. ρ is a continuous function denoting density. The relation between different variables in VCPN can be formulated as follows [19]:

$$\rho_i(t) = \frac{m_i(t)}{\Delta_i} \tag{1}$$

$$v_i(t) = \frac{x_i(t).\Delta_i}{m_i(t)} \tag{2}$$

$$\frac{d\rho_i(t)}{dt} = \frac{1}{\Delta_i}\frac{dm_i(t)}{dt} \tag{3}$$

$$\frac{dm_i(t)}{dt} = x_{i-1}(t) - x_i(t) \tag{4}$$

$$x_i(t) = x_{\max i}.\min\left(\alpha_i, m_i(t), C_{i+1} - m_{i+1}(t)\right) \tag{5}$$

$$x_{\max i} = \frac{v_{free\,i}}{\Delta_i} \tag{6}$$

$$\alpha_i = \frac{q_{\max i}.\Delta_i}{v_{free\,i}} \tag{7}$$

$$C_i = \rho_{\max i}.\Delta_i \tag{8}$$

Thus, a huge highway can be modeled. Every segment is characterized by its own density, velocity, capacity, and speed limitation. Therefore, traffic flow can be represented by VCPNs on highways.

2. 2. Intersection Modelling by Colored Timed Petri Nets In this colored Petri net modeling, four basic components are taken into consideration: signalized intersections, links, vehicles, and traffic lights. Each link shows the space between two adjacent intersections and can contain one or several lanes. That is, a signalized urban area consists of several intersections controlled by planned traffic lights and has a number of links gathered in the set $L = \{L_i | i = 1,...,I\}$. The links are divided into three main categories: input, intermediate, and output links. Each general link with a pertained length has a limited capacity of vehicles $C_i > 0$. which denotes the number of Passenger Car Units that the link can handle at the same time. Therefore, each link may be divided into C_i cells based on unit capacity. It is also necessary to consider the physical space which each vehicle occupies while crossing the intersection. It is assumed that each cell's capacity is 1.

Traffic Networks (TNs) are modeled using two types of Petri nets in the simulation. The intersections of the traffic network are represented by a Colored Timed Petri Net (CTPN), and traffic lights are represented by a Timed Petri Net (TPN). Traffic lights are considered to pertain to a common signal timing plan. A TPN is defined as a digraph $TPN = \{P, T, Pre, Post, FT\}$ in which P represents a set of places, T represents a set of transmissions, Pre and Post are the pre-incidence and post-incidence matrices and FT is the firing time vector. FT specifies the deterministic duration of the firing of each transition. Colored Timed Petri Nets (CTPNs) are defined as a digraph $CTPN = \{P, T, C_0, Pre, Post, FT\}$, in which we can consider all of the same elements with the TPN and C_0 as different colors. Furthermore, T is a set of timed transitions representing the flow of vehicles between successive cells.

The value of FT_j pertaining to each transition is equal to the average time interval at which each vehicle moves from one cell to another or occupies it. This value depends on the average speed of the vehicle. The firing times are equal to the times when vehicles can enter the network. In addition, a colored token is indicative of a vehicle. The color of each token is equal to the routing assigned to each vehicle. This routing indicates the different paths that a vehicle can travel, starting from a particular position.

The Petri net model of the three links' traffic lights is shown in Figure 2.

In the initial state, the token is located in m_0, then the token is transited to m_1 and the traffic light color is changed to the color of the corresponding place. The successive steps take place similarly until a cycle completes and reaches the initial state.

Moreover, the TPN model of the traffic light controller is depicted in Figure 3 in accordance with Table 1. Also, the controller operating process is shown in Figure 4.

2. 3. Timed Petri Net Model of Traffic Lights

The traffic lights of a traffic network must be defined in accordance to a signal timing plan. This signal timing

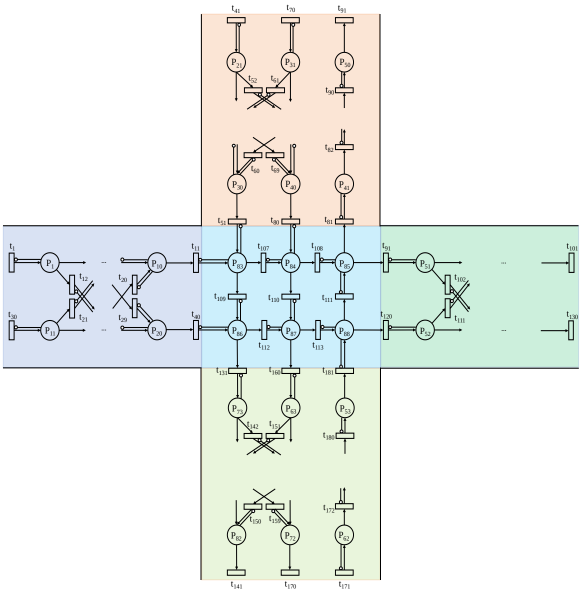


Figure 2. CTPN modelling the simulated intersection

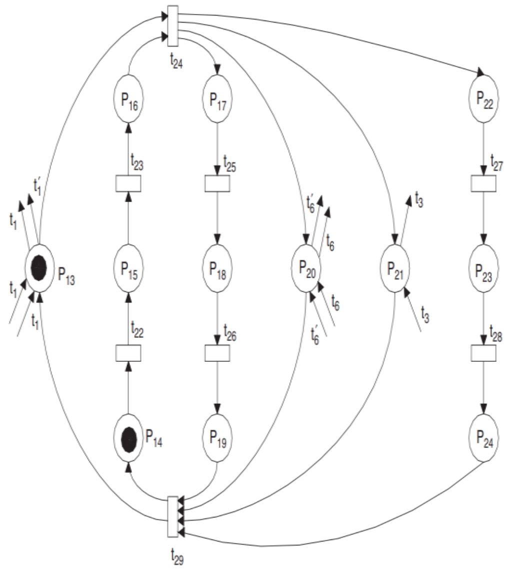


Figure 3. The TPN Modeling of the Traffic Light Controller of Intersection

TABLE 1. Signal Timing Plan of Represented Intersection

			Phases					
		Links	1	2	3	4	5	6
	1, 2	1						
Streams	5	3						
	3, 4	6						
Phase Duration [s]			τ_1	τ_2	τ_3	τ_4	τ_5	τ_6
Cycle Duration [s]			CT					

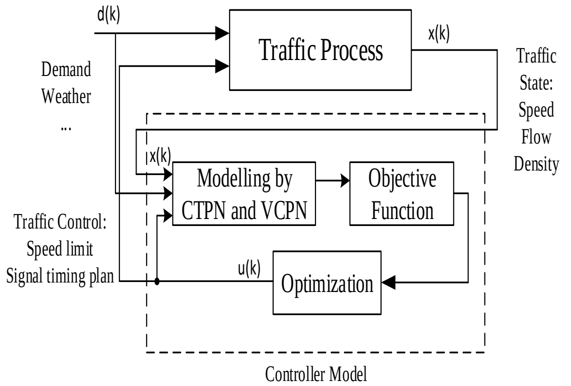


Figure 4. The way of applying the control signal to the system

plan has three phases including red, yellow and green used in Iran. Green, red and amber splits are the decision variables in the timing plan.

Cycle Time is defined as the duration of time from the center of red phase to the center of the next red phase. Furthermore, Green split for a signal is the fraction of the cycle time when the light is green in a certain direction.

The phase is defined as the time interval during which a given combination of traffic signals in the area is unchanged. The definition of the $TPN = \{P, T, \mathrm{Pr}\,e, Post, FT\}$ is utilized to model the traffic light controller. The places P and transitions, T, demonstrate the green, yellow, and red phases and their succession.

In order to obviously clarify the proposed method to model a generic signal timing plan, Table 1 shows a sample timing plan of the intersection's traffic lights. According to the table, the time of green phase for the traffic lights of link 1, 3 and 6 can be tuned by intelligent algorithms discussed in this paper. For the sample intersection, the streams allowed to proceed during the phases of the signal timing plan are depicted in Figure 3. These streams are numbered from 1 to 6. Moreover, the fixed signal timing plan consists of 6 phases as depicted in Figure 5.

2. 4. Connection Modelling by VCPN As mentioned before, in this paper a highway and the intersections are modeled by VCPN and CTPN, respectively. In fact, they can be considered as modules and can be connected together in order to constitute a specific part of traffic network in a city. Connections are used to join highways and intersections. The highway exits connect to intersections via paths called off-ramp while intersections connect to highway entrances via road junctions called on-ramp. Additionally, the connection between two intersections is created by a street called junction. It should be noticed that off-ramp, on-ramp and road junction are modelled by VCPN.

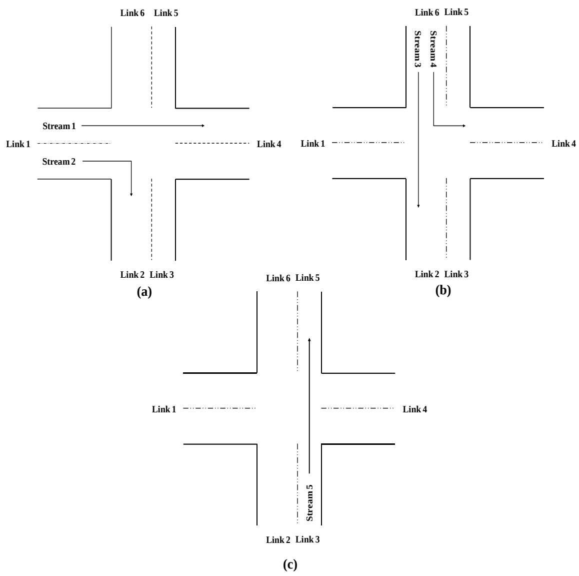


Figure 5. The Streams of the signal timing plan controlling the intersection (a) The Streams of Link 1 (b) The Streams of Link 6 (c) The Streams of Link 3

3. TRAFFIC NETWORK DESCRIPTION

Based on the modeling described before, a modular Petri nets model is proposed to describe a traffic network. To be more precise, the TN can be divided into the following sections: Highway and intersections. These sub-sections are then interconnected to create the model of the sample traffic urban network.

In this section, an urban network used to implement the proposed method is described. The sample traffic urban network is shown in Figure 6. It consists of a part of a six segments highway having a 3 km length and three lanes in aggregate. It includes three junctions considered to be juxtaposed to each other and two ramps with two lanes connecting the highway to the junctions as well. The distance between junctions and the length of both ramps is equal and about 500 m. Although cars and buses can enter this urban section via the north and south intersections, the main entrance of this urban network is located at the beginning of the highway. The entering cars can take two routes; the highway and the off-ramp. It is assumed that about 80 percent of total input cars pass the highway while only 20 percent take the off-ramp.

The traffic control of each segment is implemented using speed limitation. As mentioned before, the traffic flow in the highway can be modeled by VCPN in which various segments of the highway can be characterized by their own characteristics such as density, capacity, speed limitation, and flow rate. Additionally, the highway comprises an off-ramp road for transit vehicles to the first intersection. The input cars to the off-ramp are a fraction of the total input to the highway. On the other hand, the on-ramp road connects the third intersection to the end of

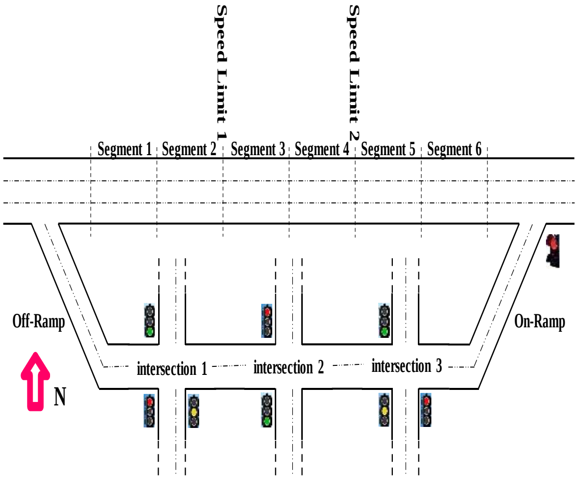


Figure 6. The Sample Traffic network

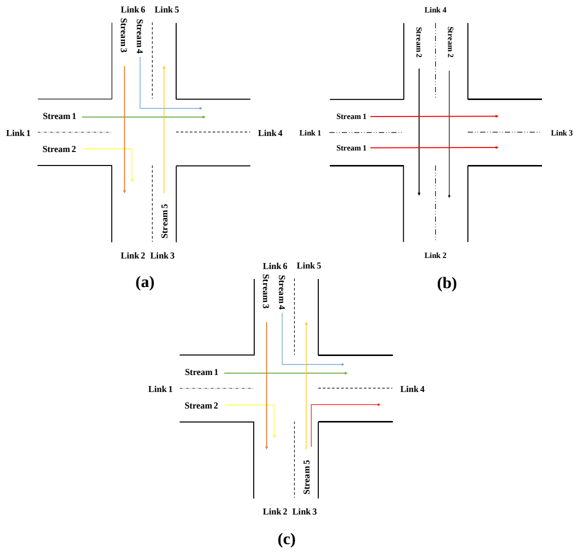


Figure 7. The Streams and links of intersections (a) intersection 1 (b) intersection 2 (c) intersection 3

the highway. Both ramps are modeled by VCPN. The street located between the intersections can be considered as one or more sections and modeled by VCPN. Therefore, the urban network possesses six segments, two ramps, and two streets in the aggregate, and the traffic flow in these areas can be analyzed by VCPN. In contrast, the traffic flow in all three intersections is modeled using TPN and controlled by setting a signal timing plan. In the first intersection, there are three input links called links 1, 3, and 6. Links 1 and 3 possess two streams, while link 6 has one stream used for only BRT. The buses just take Link 5 to depart from the intersection. Links 2,4, and 6 are considered as the intersection output. Figure 7(a) illustrates the intersection associated with streams of cars. The second intersection, located in the middle of the urban area, is an ordinary one that personal cars enter via link 1, as shown in Figure 7(b). The third intersection resembles the first intersection, except that there is no special route for BRT. In other words, the car moving in-stream five can keep right or straight, as shown in Figure 7(c).

4. OPTIMIZATION ALGORITHM

In this section, the proposed traffic system control flowchart is presented. Such a structure must be able to optimize traffic flow by setting the time of traffic light phases in intersections and speed limitation in highways under different normal hours and abnormal conditions.

As stated before, this optimization method aims to minimize the number of occupancy in the considered urban area after a specific period of time by setting signal timing plans of traffic lights in all three intersections and speed limitations in different segments of the highway. In fact, we face an optimization problem in which the objective function is the number of occupancies in the urban area, and decision variables are the time of each phase in all of the three intersections and speed limitation in every segment of the highway. In this section, the optimization problem will be formulated. The value of the objective function can be defined as follows:

$$\begin{aligned} OF = {} & \sum_{i=1}^{N\_Seg} Nc\_seg(i) + Nc\_\mathrm{junc}12 + \\ & Nc\_\mathrm{junc}23 + Nc\_\mathrm{on\_ramp} \\ & + Nc\_\mathrm{off\_ramp} + \sum_{i=1}^{N\_\mathrm{Junc}} Nc\_\mathrm{junc}(i) \\ & + VarOnRramp + VarSpeedSegL\mathrm{im}\,2 \\ & + VarSpeedSegL\mathrm{im}\,4 \end{aligned} \tag{9}$$

$$\begin{aligned} & VarSpeedSegLim2 = \alpha_{Speed\_\mathrm{lim}\_2} \times \\ & \left(r_{speed\_\mathrm{lim}\_2}(t) - r_{speed\_\mathrm{lim}\_2}(t-1)\right) \end{aligned} \tag{10}$$

$$\begin{aligned} & VarSpeedSegLim4 = \alpha_{Speed\_\mathrm{lim}\_4} \times \\ & \left(r_{speed\_\mathrm{lim}\_4}(t) - r_{speed\_\mathrm{lim}\_4}(t-1)\right) \end{aligned} \tag{11}$$

$$\begin{aligned} & VarOnRamp = \alpha_{on\_ramp} \times \\ & \left(r_{on-ramp}(t) - r_{on-ramp}(t-1)\right)^2 \end{aligned} \tag{12}$$

where $Nc\_seg(i)$ and $Nc\_\mathrm{junc}(i)$ denotes the number of vehicles in the highway segments and junctions at the end of the time horizon (t_{end}) respectively and the index i denotes the number of segments and intersections. Additionally, since variation of speed limitation in each step time can disrupt urban order, two terms are considered as penalty for changing the speed limitation on segments 2 and 4, denoted by $VarSpeedLimSeg2$,

$VarSpeedLimSeg4$. They are calculated in Equations (10)-(11). On the other hand, the traffic light installed on the on-ramp must rarely change the ratio of green and red phases in every step time. Therefore, when this ratio changes, a penalty must be imposed on the objective function. This penalty is denoted by $VarOnRamp$ and calculated according to Equation (12). $\alpha_{Speed\_lim}, \alpha_{on\_ramp}$ are considered as weight factors. Also, the sum of occupancy between junctions 1, 2 and 3 and both ramps must be added to the objective function. According to Equation (9), it is obvious that the optimization problem aims to minimize the number of remaining cars in the urban area without changing the speed limit in the highway and the control signal in the on-ramp traffic light.

The various steps of the flowchart are given as follows:

Algorithm1:

Input: Length, Free Speed, Maximum Speed, Max Density, Critical Density, Maximum Flow Rate, Maximum Capacity and Number of Highway Segments and Set of Places, Transitions and Colors and Pre-incidence and Post-incidence matrices.

Output: Speed limitation on segments 2 and 4, signal timing plan of the intersections.

Step 1: Initialize the preliminary data including Length, Free Speed, Maximum Speed, Max Density, Critical Density, Maximum Flow Rate, Maximum Capacity and Number of Highway Segments and Set of Places, Transitions and Colors and Pre-incidence and the Post-incidence matrices.

Step 2: Initialize the number of input cars in various scenarios and periods of time

Step 3: Assign the initial population of decision variable containing signal timing plan of traffic lights in three intersections and speed limitations in segment 2 and 4 in the highway randomly for first step time.

Step 4: Run PSO algorithm to find the most optimized solution in the first step time

Step 5: Run the PSO algorithm again to find the best solution for the next step time. Consider the final status of the best solution in the previous step time as the initial status of urban network for the next step time.

Step 6: Go to step 5 if there is a next step time, otherwise go to 7.

Step 7: Save the best solution and end.

5. SIMULATION RESULTS

In order to evaluate the control system efficiency proposed in this paper, a comparison study is conducted between the proposed model traffic controller and no control condition. In the proposed traffic controller model, the Signal Timing Plan of intersections and on-ramp and speed limit in the highway are set using a Particle swarm (PSO) algorithm aiming to minimize the number of occupancies in the urban area. In contrast, it is supposed that the Signal Timing Plan in no control condition is fixed and unchanged. In other words, Signal Timing Plan and the speed limit are optimized according to the traffic volume. Five different types of scenarios are considered in order to evaluate the control system's performance. They are called normal hour, rush hour, midnight hour, rainy weather conditions, and accident hours. MATLAB software is utilized for simulation. The different scenarios mentioned above will be described in the following section in detail, and simulation results will be presented under these scenarios.

5. 1. Rush Hours Scenario Traffic flow during rush hours is one of the most challenging issues in the urban traffic system. In this period of time, as illustrated in Table 2, most intersections and highways in the city are occupied and congested by a large number of vehicles. This causes considerable air pollution and waste of time. For this reason, traffic flow control is much more important in these hours .

Traffic flow in the sample urban area is considered in this subsection, and the traffic control system is optimized by the proposed method. The number of cars arriving at different parts of urban areas within 15 minutes has a Poisson distribution with parameters tabulated in Table 2. As mentioned before, the total simulation time is 2 hours; consequently, this period of time is divided into 8 equal periods lasting 15 minutes. As expected, this table shows that the rate of input cars is significantly high in this period of time. Figure 8 illustrates the average number of cars in different areas in the traffic network. Figure 9 illustrates the status of the traffic network at 11:15 for both cases of optimization control method and fixed signal timing plan. The results clarify the advantage of applying the optimization method to set the timing signal of traffic lights in the intersection and on-ramp and the speed limit on the highway. The comparison between the two cases shows that when the number of input cars grows during rush hours, the proposed method can considerably enhance the traffic flow.

5. 2. Normal Hours Scenario In this scenario, it is assumed that the number of input cars and, consequently, the traffic volume is mediocre. This period of time refers to the midday hours, typically between 11 and 13. The average number of input cars in this period of time is reported in Table 3. The simulation result shows that the number of cars in the optimized control in all parts is lower than in the no-control condition, and the optimization control system can considerably increase the traffic flow rate of the network. Generally speaking, the results verify that the optimization control system can reduce the number of remaining cars rather than the no-control conditions in normal hours.

TABLE 2. Real traffic data in rush hours

	Highway Entrance	Intersection I Link 6	Intersection I BRT (Link 3)	Intersection II Link 4	Intersection III Link 6	Intersection III Link 3
19:00 - 19:15	1100	800	15	700	500	250
19:15 - 19:30	1300	600	12	700	600	200
19:30 -19:45	1450	700	14	650	400	300
19:45 - 20:00	1500	680	16	680	480	280
20:00 - 20:15	1500	630	18	500	550	290
20:15 - 20:30	1300	650	13	400	580	310
20:30 -20:45	1200	670	11	400	480	340
20:45 - 21:00	1000	600	9	300	380	200

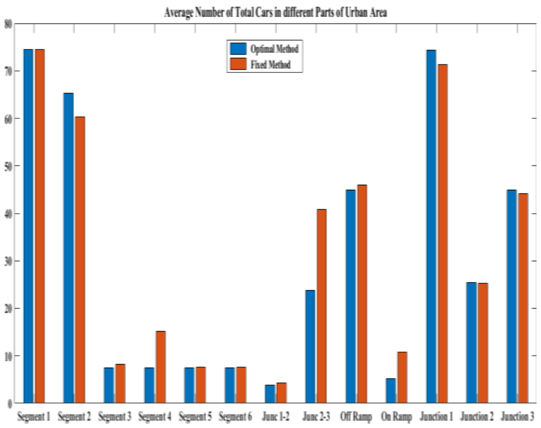
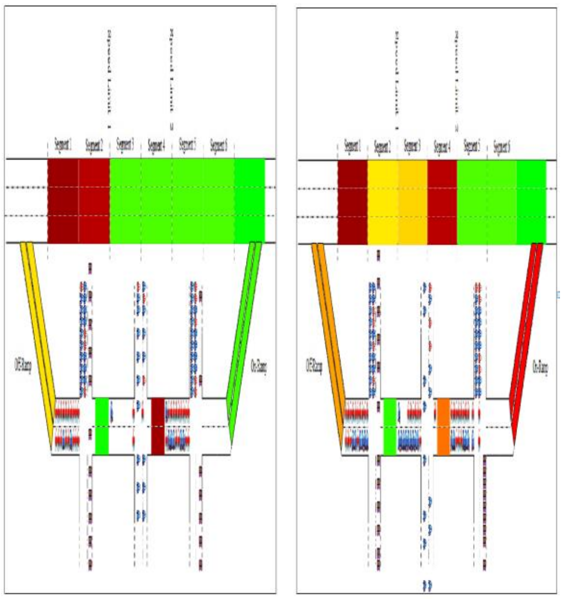


Figure 8. Average Number of Cars in Different Areas in Traffic Network

5. 3. Midnight Hour Scenario Despite the low number of cars in these hours, the control system performance for both cases is compared in this scenario. The simulation results show that because of the low traffic flow at midnight hours, the optimization of the



(b) (a)

Figure 9. Status of traffic network at 12:00 (a) Optimal Method (b) Fixed Method

TABLE 3. The average number of input cars in normal hours

	Highway Entrance	Intersection I Link 6	Intersection I BRT (Link 3)	Intersection II Link 4	Intersection III Link 6	Intersection III Link 3
11:00 - 11:15	700	300	9	240	140	100
11:15 - 11:30	800	250	7	250	180	120
11:30 -11:45	900	280	6	270	220	140
11:45 - 12:00	850	330	5	210	210	125
12:00 - 12:15	780	310	6	265	265	145
12:15 - 12:30	800	275	7	200	200	170
12:30 -12:45	750	240	7	180	180	135
12:45 - 13:00	810	250	8	150	150	155

control system has a negligible effect on the amount of traffic in the urban area. In other words, whether the timing signal traffic light and the speed limit are optimized or not, the traffic flow will be acceptable. Therefore, there is no necessity to use the proposed method in this period of time. The average number of input cars in this period of time is reported in Table 4.

5. 4. Rainy Weather Condition Scenario Rain can slip the surface of streets. Hence, drivers have to drive much more carefully and reduce their speed. As a result, traffic flow increases in the rainy weather condition significantly. Under these conditions, the control system performance is evaluated when both cases are applied. It is supposed that in a specific period of time, the number of input cars increases suddenly, and the traffic network is congested. The data of input cars in this scenario is given in Table 5.

The comparison between Tables 5 and 2 shows that the number of input cars between 11:30 and 12:15 increases by 15%. Similarly, the simulation results show that the optimization method can untie the traffic node under this condition. This means that the proposed method can be used even in critical situations like rainy weather.

5. 5. Accident Scenario In this scenario, it is supposed that an accident happens in segment five on the highway at 11:45 and lasts for 15 minutes. It is obvious that the flow rate of vehicles decreases because at least two main streams are congested on the highway. Since this happens on the highway, only the traffic flow in this part of the urban area is affected. As mentioned before, traffic flow on the highway is controlled by the speed limit on segments. Therefore, the signal timing plan of traffic lights is not important in this scenario. As the simulation results show in Figure 10 When speed limits in segments 2 and 4 are set appropriately, congestion caused by accidents can be reduced. In fact, speed limitation in the segments before the accident must be reduced while speed limitation in the next segments must be increased.

TABLE 4. The average number of input cars at midnight hours

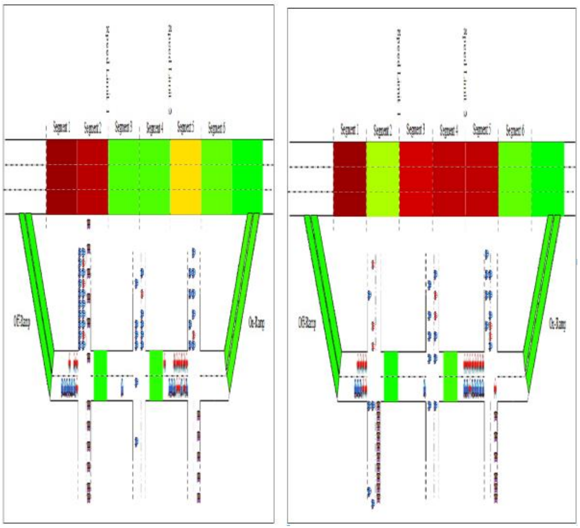
	Highway Entrance	Intersection I Link 6	Intersection I BRT (Link 3)	Intersection II Link 4	Intersection III Link 6	Intersection III Link 3
11:00 - 11:15	260	80	1	70	80	80
11:15 - 11:30	250	60	0	70	60	60
11:30 -11:45	230	70	1	65	70	70
11:45 - 12:00	220	68	0	68	68	68
12:00 - 12:15	210	63	1	50	63	63
12:15 - 12:30	200	65	0	40	65	65
12:30 -12:45	180	67	1	40	67	67
12:45 - 13:00	190	60	0	30	60	60

TABLE 5. The data of input cars in Rainy weather condition

	Highway Entrance	Intersection I Link 6	Intersection I BRT (Link 3)	Intersection II Link 4	Intersection III Link 6	Intersection III Link 3
11:00 - 11:15	700	300	9	240	140	100
11:15 - 11:30	800	250	7	250	180	120
11:30 -11:45	1200	400	6	400	410	250
11:45 - 12:00	1100	450	5	350	400	270
12:00 - 12:15	1000	420	6	410	430	240
12:15 - 12:30	800	275	7	200	200	170
12:30 -12:45	750	240	7	180	180	135
12:45 - 13:00	810	250	8	150	150	155

TABLE 6. Performance Improvement of Optimization Control System

Percentage of performance improvement (%)	Normal Hours	Rush Hours	Midnight Hours	Rainy	Accident
No control	10.54	5.8233	0.1599	40.8599	20.8193
Timing signal planningoptimization (Our proposed Method)	5.23	1.24	0.004	28.15	10.54
Highway Optimozation Previous paper [19]	8.37	3.23	0.089	32.189	15.12



(b) (a)

Figure 10. Status of traffic network at 12:00 (a) Optimal Method (b) Fixed Method

6. DISCUSSION

In order to examine the proposed optimization method more, a comparison study is conducted. Four different control system methods are considered. In the first method, it is supposed that there is no control for signal timing plan in the intersections and speed limitation in the highway, and they are determined based on historical data in the intersection and highway. In the third method, it is supposed that the urban traffic network model proposed by Dotoli and Fanti [10] is used to optimize only timing signal planning in the intersections. In this paper, a modular framework based on colored timed Petri nets (CTPNs) is presented to represent the dynamics of signalized TN systems: places modeling link cells intersections, tokens are vehicles and token colors .

Demonstrate the routing of the corresponding vehicle. In addition, ordinary timed Petri nets model the signal timing plans of the traffic lights controlling the area. The proposed modeling framework is applied to a real intersection. In contrast, in the third method, continuous Petri nets models proposed by Tolba et al. [19] for the analysis of highways are used. This model is proposed for the analysis and control design in highways. Under this condition, speed limitation on highways is just optimized. In the last control system, the traffic control flow is fully optimized using a signal timing plan in the intersections and speed limitations on the highways.

Table 6 tabulates the percentage of performance improvement of these four optimization control system methods. As expected, the simulation results show that when the optimization process is implemented for the whole of the system, the percentage of performance improvement is considerably higher. Additionally, when the signal timing plan is just optimized, the traffic flow is conducted more effectively in comparison with speed limitation optimization

7. CONCLUSION

In this paper, a modular framework is proposed to model the traffic flow of the Highway and intersections. The modeling procedure for the intersections is based on Timed Petri Nets, while Continuous Petri Nets with Variable speeds are used to model the highway networks. The timing of traffic lights and variable speed limits on the Highway were optimized by a PSO, and the status of the urban network area was compared in both optimization and fixed control conditions. Six various scenarios, including rush hours, normal hours, midnight hours, rainy weather, and accident occurrence, were considered to completely examine both conditions. The simulation results showed that when traffic control is optimized, the number of occupancies can be reduced in special conditions such as rainy weather and accident occurrence. In contrast, when traffic flow is extremely high or low, like rush and midnight hours, control flow optimization is not able to improve traffic flow in the city.

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Persian Abstract

چکیده

در این مقاله کنترل یکپارچه بزرگراه ها و تقاطع ها مورد بررسی قرار گرفته است. یک چارچوب مبتنی بر شبکه پتری مدولار برای مدل‌سازی جریان ترافیک بزرگراه‌ها و سیستم‌های شبکه ترافیک شریانی پیاده‌سازی شده است. در این چارچوب، چراغ‌های راهنمایی تقاطع شریانی توسط شبکه‌های پتری زمان‌بندی شده (TPN)مدل‌سازی می‌شوند. زمان‌بندی چراغ‌های راهنمایی و محدودیت‌های سرعت متغیر در بزرگراه با استفاده از یک الگوریتم هوشمند بهینه‌سازی می‌شود. این الگوریتم مبادله ای بین طول صف وسایل نقلیه در بزرگراه و رمپ ورودی و طول صف در تقاطع پس از هر چرخه زمانی ارائه می دهد. عملکرد کنترل کننده ترافیک بهینه و کنترل ثابت مقایسه شد. نتایج شبیه‌سازی تأیید می‌کند که استفاده از روش‌های بهینه‌سازی برای مدیریت زمان‌بندی چراغ‌های راهنمایی در تقاطع‌ها و محدودیت سرعت در بزرگراه‌ها می‌تواند به طور قابل‌توجهی جریان ترافیک را در شرایط خاص مانند هوای بارانی و تصادفات بهبود بخشد. علاوه بر این، این روش می تواند به طور قابل توجهی جریان ترافیک را در ساعات عادی افزایش دهد، در حالی که در ساعات شلوغی و نیمه شب، چنین بهبودی ناچیز است