

A Traffic Congestion Avoidance Algorithm with Dynamic Road Pricing for Smart Cities

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Abstract—The traffic congestion problem is a common issue for the residents of metropolises. Although expanding the capacity of transportation systems and stimulating the public transportation may decrease the traffic congestion, they cannot completely solve the traffic congestion problem. As a solution for the worsening traffic congestion problem in urban areas, road pricing systems have been employed. In this paper, we propose a radically different road pricing scheme to prevent and decrease the traffic congestion in metropolises. Unlike designating a small congestion charge zone in a city, we propose to employ a road pricing system over the entire city. Thus, our road pricing system can control the traffic flow in the entire traffic network of the city. Furthermore, the road prices are adjusted dynamically based on the instantaneous traffic densities of each road in the city in order to rapidly and efficiently control the traffic flow and to prevent the traffic congestion. Moreover, we propose to change the road prices according to the past usage statistics of the road by predicting a possible congestion. The simulation results of our road pricing algorithm show that traffic congestion is prevented over the entire traffic network and the traffic densities of the roads are homogenized.

I. INTRODUCTION

In urban areas, worsening traffic congestion is a common problem for many metropolises and their residents. At the starting and ending times of work each day, traffic congestion significantly increases, and drivers lose several man-hours while waiting at traffic. Furthermore, the fuel consumption in congested traffic is increased by about 80% compared to the free traffic conditions [1]. Thus, the traffic congestion results in a significantly higher CO₂ emission and air pollution. In [2], it is shown that vehicles stuck in traffic pollute three times as much as those purring along motorways. Moreover, the increase in the fuel consumption due to the traffic congestion increases the current account deficit. There are several reasons of the worsening traffic congestion problem such as increase in both population and vehicle ownership in metropolises, and insufficient road capacities. Although tempting the public transportation and expanding the capacity of the transportation systems may reduce the traffic congestion, they are not sufficient to completely solve the traffic congestion problem [3].

Road pricing is proposed to solve the traffic congestion problem for the first time in [4]. The road pricing scheme is based on making usage of congested routes more expensive than the routes with normal traffic density [4]. Several theoretical road pricing models are presented in [5], [6]. For the first time, the road pricing scheme is realized in Singapore in 1976

[7]. In that scheme, the toll fees of roads are variables based on the traffic congestion levels. The road pricing scheme in Singapore reduced the traffic density by 76% [7]. Afterwards, the road pricing systems are employed to manage traffic congestion in several metropolises. For example, in Milan, a zone-based road pricing is employed; that is, vehicles entering this charging zone pays a toll fee regardless of their pollution level [8]. Furthermore, a zone-based road pricing is used in London; however, vehicles that enter the congestion charge zone incur a charge according to their pollution level [9]. After implementation of the road pricing system in London, the traffic density in the charge zone is decreased by 60% [9].

In this paper, we present a radically different road pricing model to prevent and reduce the traffic congestion in urban areas. Unlike designating a small congestion charge zone controlled with a few toll booths at the zone entrances, we consider a congestion control system with RFID-based electronic toll booths available at each road junction. Therefore, our road pricing model can be easily extended over the entire road network of the city. Furthermore, the road prices are adjusted dynamically based on the instantaneous traffic densities of each road in the city in order to instantaneously control the traffic flow and to prevent the traffic congestion. For the efficiency of the dynamic road pricing algorithm, it is crucial that the drivers must know the dynamic road prices before they arrive a junction. Thus, inter-vehicle communication (IVC) can be successfully used for the transmission of the road prices to the drivers. There are several protocols proposed for an efficient IVC [10]. For example, in [11], a GPS-based message broadcasting system for IVC is presented, and in [12], an adaptive delay-sensitive and congestion-aware system based on beaconing is introduced.

The dynamic road pricing facilitates the management of the traffic densities of the roads in the entire traffic network. In other words, an increase in the traffic density of a road increases the toll fee of this road; hence, the traffic congestion in this road can be prevented before it takes place. In addition, we propose to change the road prices according to the past usage statistics of the road. That is, the toll fee of a road is proportional with the popularity of this road. Then, to be able to use the past usage statistics, our dynamic road pricing system utilizes machine learning algorithms. The road pricing system proposed in this paper homogenizes the traffic densities over the entire traffic network.

The rest of the paper is organized as follows. In Section II, we present the dynamic road pricing model. In Section III,

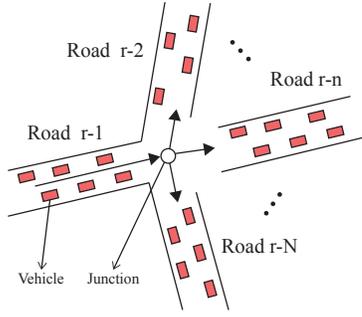


Fig. 1. The junction model of the traffic network.

the dynamic road pricing algorithm and its simulation results are presented. Finally, Section IV concludes the paper.

II. DYNAMIC ROAD PRICING MODEL

In this section, in order to present the dynamic road pricing model, we first need to define the traffic density of a road in a network. Considering the fundamental junction model of the traffic network illustrated in Fig. 1, we can express the traffic density of road $r - n$ at time t as follows

$$d_n(t) = \frac{N_n(t)}{C_n} \quad (1)$$

where $N_n(t)$ is the number of vehicles in the road $r - n$ at time t and C_n is the capacity of this road. We define the capacity as the maximum number of vehicles in which travel the road with optimal traveling time duration. Accordingly, the traffic density on the road $r - n$ at time $t + \tau$ can be given in terms of $d_n(t)$ as follows

$$d_n(t + \tau) = d_n(t) + \frac{\sum_{k=1}^{N_1^{t,t+\tau}} b_{1,n}^k}{C_n} - \frac{N_n^{t,t+\tau}}{C_n} \quad (2)$$

where $N_k^{t,t+\tau}$ is the number of vehicles that leave the road $r - k$ between time t and $t + \tau$. Assuming the vehicles in the road k are spatially homogeneously distributed, $N_k^{t,t+\tau}$ can be given as

$$N_k^{t,t+\tau} = N_k(t) \frac{v_k(t)\tau}{L_k} \quad (3)$$

where $v_k(t)$ is the average speed of the vehicles in the road $r - k$ at time t and L_k is the length of the road $r - k$. In (2), $b_{1,n}^k$ is the Bernoulli random variable indicating whether the k th vehicle leaving the road $r - 1$ follows the road $r - n$ and the probability that $r_{1,n}^k = 1$ is $p_{1,n}^k$, i.e., $b_{1,n}^k \sim B(p_{1,n}^k)$. That is, if $b_{1,n}^k = 1$, the k th vehicle leaving the road $r - 1$ follows the road $r - n$; otherwise, it follows an alternative road. $p_{1,n}^k$ depends on several road selection criterions of a driver and it can be described as

$$p_{1,n}^k = f_{1,n}^k(D_k(t), T_k, I_k) \quad (4)$$

where $D_k(t)$ is the destination parameter of the k th vehicle, T_k is the vehicle type parameter, and I_k is the traffic and road condition knowledge parameter of the driver. These parameters indicate the road selection criterions of a driver at a junction. That is, $D_k(t)$ indicates the road selection criterion of a driver

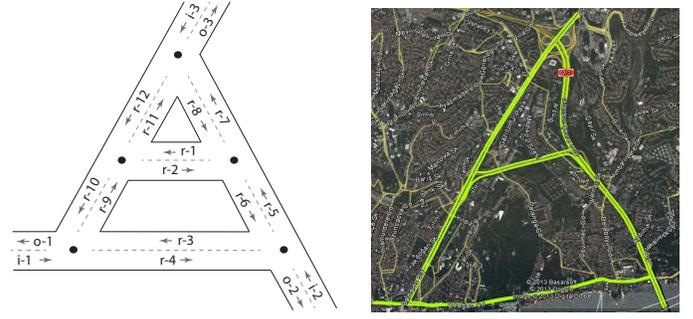


Fig. 2. The illustration of the road network in Besiktas. r , i and o denote regular, input and output roads, respectively. (Map source: Google Earth)

at a junction who wants to arrive the destination point through the shortest path. Since some vehicles have to follow a fixed route, e.g., buses and shuttles, the road selection criterion of a driver depends on the type of the vehicle, which is described by the parameter T_k . Furthermore, the road selection criterion of a driver depends on the traffic and road conditions knowledge of the driver. In other words, a driver, who knows the traffic and road conditions of the alternative roads, follows the road with the best conditions according to the driver's knowledge.

In (4), $f_{1,n}^k(D_k(t), T_k, I_k)$ is a highly complex and unknown function. In addition, $f_{1,n}^k$ function is different for each driver. To prevent and reduce the traffic congestion in each road in the traffic network, we need to control the road selection probability of each driver, i.e., $p_{1,n}^k$, by controlling $f_{1,n}^k$ function. To be able to control $f_{1,n}^k$ function, an externally adjustable global factor that affects the decision mechanism of each vehicle driver is required. Pricing the roads dynamically according to their traffic densities can be used for this purpose. That is, the toll fee of a road becomes higher as the traffic density increases in this road. Since a driver at a junction tends to follow a road having a low price, the traffic congestion at the roads with high traffic density is prevented and reduced because of the higher price of these roads. Then, $p_{1,n}^k$ becomes dependent to the road pricing factor as follows

$$p_{1,n}^k = f_{1,n}^k(D_k(t), T_k, I_k, \mathbf{M}_1(t), F_{\mathbf{M}_1}^k(t)) \quad (5)$$

where $\mathbf{M}_1(t)$ is an array of dynamic, i.e., time-variant, prices of alternative roads and $F_{\mathbf{M}_1}^k(t)$ is a factor related to the impact of the road prices on the k th vehicle leaving road $r - 1$. Relating the pricing factor $\mathbf{M}_1(t)$ to the traffic density of the roads, we can gain control over the traffic congestion as described above. For this aim, we can express the price of the road $r - n$ for a vehicle leaving the road $r - 1$, i.e., the n th element of $\mathbf{M}_1(t)$, as follows

$$M_1^n(t) = h(P_n(t), d_n(t)) \quad (6)$$

where $P_n(t)$ is the past usage statics of the road $r - n$. That is, the toll fee of the road $r - n$ is proportional with the popularity and the traffic density of this road. Because of the highly complex and stochastic nature of the model given in (5), it is hard to analytically define the effect of the money on the behavior of vehicles.

III. PERFORMANCE EVALUATION

In this section, we evaluate the performance of pricing-based congestion control system. We perform a simulation in

TABLE I. ROAD NETWORK PARAMETERS

Road Pair	Length (m)	Number of Lanes	Optimum Travel Time (s)	Optimum Speed (km/h)
r-1/r-2	1400	2	56	90
r-3/r-4	1800	3	129	50
r-5/r-6	1355	5	41	120
r-7/r-8	1035	5	31	120
r-9/r-10	1085	4	44	90
r-11/r-12	1190	4	48	90
i-1/o-1	305	3	12	90
i-2/o-2	695	5	21	120
i-3/o-3	360	4	14	90

Matlab aiming to observe the effect of pricing-based control system over a partially congested road network and focusing on the behavior of individual vehicles. Since it is impossible to entirely model the impact of pricing of roads on the route preference of vehicle users, first, we simplify the dynamic road pricing model given in Section II.

For the simulation, we consider a road network in Besiktas, which is a very crowded town of Istanbul, Turkey, where the traffic density is usually over the city average. The considered road network is illustrated in Fig. 2.

The basic characteristics of the road network along with our assumptions are listed as follows;

- The network has three pairs of input and output roads through which vehicles can enter and leave the network, respectively.
- A vehicle at any junction in the network has always two alternative roads to follow.
- The pricing is instantaneous, i.e., two vehicles that consecutively enter a road can be charged differently.
- The vehicles continuously move on the network, and are not allowed to stop at the junctions or on the road segments. We also assume that no traffic signal is present in the network.
- The users have the pricing information of only the next alternative roads when they arrive at a junction.
- The real data for the length, the number of lanes, the optimum travel time and the optimum speed for the network roads are presented in Table I.

We carry out the simulation for a full business day. Using the traffic density data for all days of a week except the weekend (26.11.2012-30.11.2012) obtained from INFOTECH Inc., a private company producing navigation solutions for vehicles, we derive a popularity matrix \mathbf{P} of the road network for each hour. The popularity index of a road in that matrix is calculated for hourly time intervals as the ratio of the average travel time of vehicles through a road segment to the optimal travel time of that road. Here, the optimal travel time refers to the travel time of a vehicle when it moves through the road at the speed limit specified for that road. In the remainder of this paper, the speed limit is referred as the optimum speed. The popularity indices denote the past usage statistics of the road at a specific hour of the day, and is analogous to parameter P in (6). Therefore, they represent the awareness of the roads by all the vehicles.

Vehicles are supplied to the network from the input roads at different rates for each hour as shown in Fig. 3. The hour-based rates are determined according to the popularity indices of the

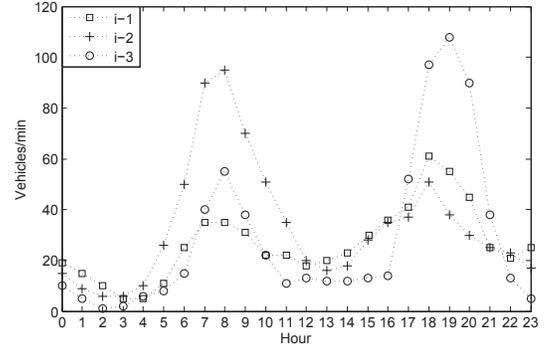


Fig. 3. The input rates of vehicles for each input road.

input roads. We assume that the vehicles aim to reach different destinations out of the network specified before supplied to the network. Since there are three output roads that connect this network to the overall city network, each vehicle aims to reach specific one of these three output roads with the purpose of ultimately arriving its destination.

In the simulation, the vehicles are supposed to avoid longer routes to reach their destinations. Incorporating the popularity indices, the probability for a vehicle at a junction to select road i from the set of alternative roads $[i, \bar{i}]$ in the network without pricing-based control can be simplified as

$$p_{k,i} = \frac{P_i(t)S_i}{P_i(t)S_i + P_{\bar{i}}(t)S_{\bar{i}}} \quad (7)$$

where i and \bar{i} denote the indices of the next alternative roads. S_i is the minimum distance that a vehicle has to travel to arrive its destination if it decides to follow the i th road. In a pricing-based controlled network, the contribution of the pricing factor on the road selection can be incorporated as follows

$$p_{k,i} = \frac{\frac{P_i(t)S_i}{M_i(t)}}{\frac{P_i(t)S_i}{M_i(t)} + \frac{P_{\bar{i}}(t)S_{\bar{i}}}{M_{\bar{i}}(t)}} \quad (8)$$

where $M_i(t)$ is the pricing coefficient of the i th road at time t , and formulated as

$$M_i(t) = P_i(t)d_i(t) = P_i(t)\frac{N_i(t)}{C_i} \quad (9)$$

Here, the capacity of the i th road, C_i , denotes the number of vehicles that can simultaneously travel safely, i.e., by keeping sufficient inter-vehicle distance, at the optimum speed on road i , and can be approximated as follows

$$C_i = h_i \frac{L_i}{r_i} \quad (10)$$

where h_i is the number of lanes on road i , L_i is the length of road i , and r_i is the inter-vehicle distance for safe drive on road i of which the magnitude is assumed to be equal to the half of the magnitude of the optimum speed on road i , and the unit is meter.

As the number of vehicles on a road segment exceeds the capacity specified for that road, we assume that the travel time of a vehicle deviates from the optimum travel time of the road as follows

$$T_{k,i,t} = (1 + d_i(t))T_{opt,i} \quad (11)$$

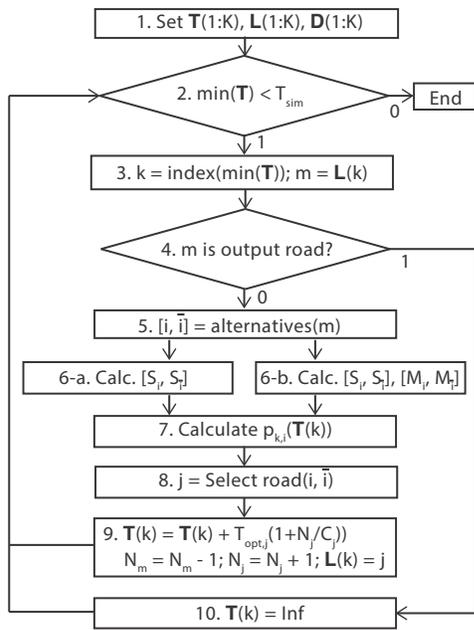


Fig. 4. Simulation algorithm for the behavior of vehicles on the network with and without pricing-based control.

where $T_{k,i,t}$ is the travel time of the k th vehicle through the i th road in case it arrives at the starting point of road i at time t , and $T_{opt,i}$ is the optimum travel time on road i .

A. Simulation Algorithm

We conduct simulations based on the algorithm demonstrated in Fig. 4 to investigate the behavior of the vehicles on the specified road network with dynamic pricing control. The algorithm basically operates through the following steps:

- 1) A time array, T , that keeps the information of when the vehicles are supplied to the network is set based on the hourly input rates of each input road. The initial locations of the vehicles are set in the location array, L . The target destination of each vehicle is set in the destination matrix.
- 2) The algorithm checks whether there is a vehicle with the last active time less than the time specified for the end of the simulation. If the active times of all of the vehicles exceed the simulation time, then the simulation ends, else it continues with the Step 3.
- 3) The index of the vehicle with the minimum active time, k , is determined. The current location of the k th vehicle is assigned to m .
- 4) The algorithm checks whether the road m is an output road or one of the input and regular roads. If it is an output road, the algorithm continues with Step 10.
- 5) If road m is not an output road, the next alternative roads for the k th vehicle on road m , $[i, \bar{i}]$, are determined.
- 6) The minimum travel distance for the vehicle to reach its destination is calculated for both alternatives. For the pricing-based control case, the pricing coefficient of the both alternatives is also determined using (9).
- 7) Using the popularity indices of the alternative roads and the parameters determined in Step 6, the binomial

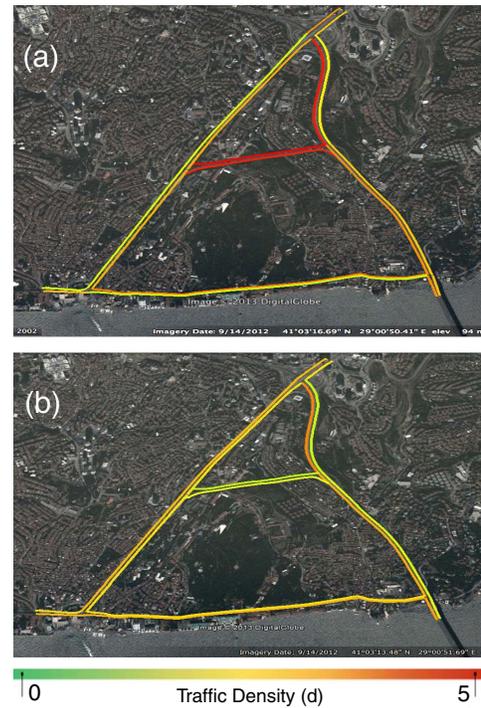


Fig. 5. The traffic density map of the network between 7-8 pm (a) without and (b) with pricing-based control (Map source: Google Earth).

probability for the next alternative roads is calculated based on (7) for the case without pricing, and based on (8) for the case with pricing.

- 8) The vehicle k randomly selects one of the next alternative roads to follow according to the probability distribution.
- 9) With the selection of an alternative road, the last active time of the k th vehicle is incremented depending on the density of the selected road j using (11). While the number of cars on road m is decremented by one, the number of cars on road j is incremented by one. The location of the k th vehicle is also updated by the j th road. The simulation continues with Step 2.
- 10) If the k th vehicle is on an output road, then the vehicle leaves the network through this road. The last active time of the vehicle leaving the network, $T(k)$, is set to infinity, and the vehicle becomes inactive. The simulation continues with Step 2.

B. Simulation Results

Based on the simulation algorithm expressed in Section III-A, the behavior of vehicles on the road network is simulated for two cases, i.e., with and without pricing. In this section, we present the results of this simulation-based performance evaluation aiming to demonstrate the effect of pricing-based control over the traffic density of the entire network.

According to the simulation results, the traffic density map of the road network between 7-8 pm is illustrated in Fig. 5(a)-(b), without pricing and with pricing, respectively. The density map in Fig. 5(a) reveals that without a pricing-based control, there are several roads stuck with congestion problem. However, during the same time interval, some of the

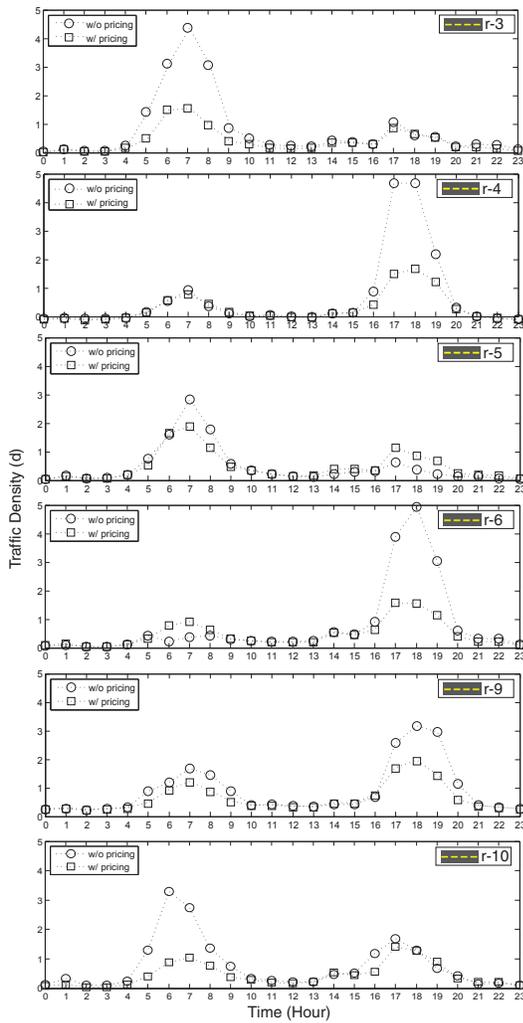


Fig. 6. The traffic density of main roads in the network during a whole business day with and without pricing-based control.

roads have very low traffic density. On the contrary, with the application of the pricing algorithm, the Fig. 5(b) shows that the traffic density on the overall network is distributed almost homogeneously. That is, while the traffic density of the roads with high congestion is reduced, the roads with low traffic density becomes more crowded.

Fig. 6 demonstrates the traffic density of the main roads of the same network during a whole business day with and without pricing-based control. The amelioration of the traffic density on the highly congested roads is clearly shown. For example, the traffic density of roads r-4 and r-6 between 4-8 pm is reduced from 5 to below 2. It is also demonstrated that on some roads the traffic density is increased with the pricing-algorithm, for instance, the density of road r-5 between 4-8 pm and the density of road r-6 from 6-8 am is slightly increased. Overall, the density of each road stays below 2 with the pricing-algorithm underlining the functionality of the algorithm for homogeneous distribution of traffic.

Although the traffic density is increased on some roads, overall, the average travel times of the vehicles between their roads and destinations are significantly decreased. Table II

TABLE II. AVERAGE TRAVEL TIMES BETWEEN INPUT ROADS AND DESTINATIONS

Interval (Hour)		Route					
		i1-o3	i1-o2	i2-o1	i2-o3	i3-o1	i3-o2
6-9	w/o Pricing	529s	353s	320s	323s	399s	362s
	w/ Pricing	308s	276s	262s	232s	239s	243s
10-16	w/o Pricing	191s	229s	220s	175s	246s	180s
	w/ Pricing	176s	190s	204s	157s	210s	162s
17-20	w/o Pricing	286s	654s	396s	389s	670s	439s
	w/ Pricing	224s	402s	286s	253s	371s	253s
21-5	w/o Pricing	146s	209s	223s	179s	240s	212s
	w/ Pricing	134s	192s	172s	134s	200s	145s

presents the average travel times of the vehicles supplied from the input roads aiming to reach their destinations, i.e., output roads. The reduced travel times clearly indicate that the vehicles are not led by the pricing-algorithm to redundantly move around in the network.

IV. CONCLUSION

In this paper, we investigate a novel road pricing model to prevent and reduce the traffic congestion in urban areas. Unlike using a road pricing scheme over a small zone in a city, we propose to employ a road pricing system over the entire city. Thus, our road pricing system is able to control the traffic flow over the entire the traffic network of the city. The road prices are changed dynamically according to both the traffic densities and popularities of the roads in the network to instantaneously control the traffic flow and to prevent the traffic congestion. The simulation results show that the pricing-based traffic control algorithm proposed in this paper homogenizes the traffic densities over the entire traffic network and the traffic congestion can be prevented before it takes place.

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