Reasonable traffic network model and flexible traffic control strategy play important roles in improving the urban traffic control efficiency. Introducing granular computing theory into traffic network modeling and traffic control is a useful attempt, since granular computing is closer to the human thinking in solving problems. In this paper, the traffic elements are depicted using S-rough set to achieve the granulation partition of traffic network. Four layers are partitioned in the proposed hierarchical multigranularity traffic network model, such as vehicle layer, platoon layer, segment and intersection layer, and subregion layer. Each traffic granule is represented in rough representation form, and the dynamic characteristics are described using the elementary transfer operations based on S-rough set theory. As an application on the proposed traffic network model, an extended max-pressure traffic control strategy is applied on the platoon and segment and intersection layer. Simulation results illustrate that the proposed traffic network model and traffic control strategy achieve better performance.

1. Introduction

Congestion has become a major problem in urban traffic systems. Reasonable traffic data management and optimal traffic control strategy play an important role in traffic control system [1]. With the development of data collection technologies, more and more traffic data can be collected using for design the traffic control strategy. How to make full use of the massive traffic data is an essential issue in traffic control and management system, including vehicle information, platoon information, road segment information, and subregion information. Furthermore, based on the reasonable traffic data process and management model, how to design an optimal traffic control strategy is the other important problem. The resolutions of the two essential questions can improve the efficiency of urban traffic control system. In this paper, we try to build a hierarchical multigranularity traffic network model to depict and manage the traffic elements in urban traffic system using granular computing theory and then design a max-pressure traffic light control strategy based on the proposed model to improve the efficiency of urban traffic control system.

On the other hand, the idea of granular computing is consistent with the human thinking and problem solving way [2, 3], it has attracted more attention of researchers for intelligent transportation system. Granulation involves decomposition of whole into parts and complex problem can be decomposed into several subtasks for efficiency improving and problems simplification [4]. From this view, if the urban traffic network is viewed as multilayer and multigranular model using granular computing theory, it may be an effective way to solve the traffic control and management problems. As discussion in [5], traffic information processing and representation are the basis of urban traffic control and management. The proper construction of traffic information granules and granularity selection enable us to obtain more intuitive and accurate traffic information. In order to achieve the granulation in traffic data processing, Seng et al. analyzed the basic theory of granular computing and discussed the applications of granular computing in the intelligent...
transportation system. In their paper, the granulation method was presented based on rough set theory [6]. Yao et al. detected the traffic congestion on the city road network using granular computing in their paper. They constructed the hierarchical congestion recognition model and optimized the granular level and granularity of congestion through space conversion [7]. Li et al. introduced rough set theory and granular computing theory into road safety indicator analysis. In their paper, the individual road safety indicators were combined into a composite indicator to reduce the dimensions of selected risk factors [8]. He et al. combined the social network and community structure to build a model with multiple granularities and levels and decomposed the complex structure of large network into different granularity spaces to search the fine-grained or coarse-grained shortest path [9]. These proposed granulation ideas and methods in traffic data processing can really reduce the complexity of problem solving in traffic control and management system.

On the other hand, the traffic data collected from different devices contains measure errors; these data may be incomplete, inaccurate, and inconsistent [10, 11]. Rough set theory as one important part of granular computing theory [12] can deal with the uncertain features of traffic data well for the traffic problem solving [13]. Researchers have applied rough set theory in intelligent transportation system area, such as traffic data processing, traffic events recognition, and traffic flow prediction, since the rough representation of traffic data can express the actual situations of traffic network, improve the accuracy of traffic information, and obtain the hiding information. In our previous research work, the rough set theory was utilized for processing the field traffic data with vagueness to extract car-following behavior decision rules and construct a data-driven car-following model [11]. Xiong et al. integrated rough set and Bayesian network for roadway traffic accident analysis [14]. Deshpande et al. combined support vector machine and rough set theory to achieve the traffic flow prediction [15]. These applications based on rough set theory show better performance in traffic data processing.

Inspired by the ideas of granular computing theory, in this paper, we granulate the traffic elements in traffic network using singular rough set theory and build a hierarchical multigranularity model to represent the urban traffic network. And, based on the traffic network model, an extended max-pressure traffic control strategy is proposed to improve the efficiency of urban traffic system. The contributions of this paper lie in two aspects: (1) The traffic network is modeled as a multilayer and multigranularity model including vehicle granule, platoon granule, and subregion granule. (2) The proposed extended max-pressure traffic control strategy computes the light phase pressure using the rough representation of platoon and segment granules, which can reflect the actual situations of traffic network.

The remainder of this paper is organized as follows. The proposed hierarchical multigranularity model is presented in Section 2. The extended max-pressure traffic control strategy is given in Section 3. In Section 4, the simulations are carried out to analyze the performance of the proposed strategy. This paper is concluded in Section 5.

2. Traffic Network Modeling Based on Granular Computing Theory

On the view of multigranularity, the world is made up of granules with different size, attributes, and states. In the real world, many complex systems can be decomposed as multiple layers and multiple granules [16]. The common granules can be extracted from the real system to simplify the complexity of problems. On this view, the urban traffic network is also a kind of hierarchical multigranularity model in reality with different types of traffic elements, such as vehicle, platoon, road segment, intersection, and subregion.

As shown in Figure 1, according to the concepts of elements in traffic network, there are four layers: vehicle layer, platoon layer, intersection and segments layer, and subregion layer. Based on the states of vehicles travelling on a road segment, they may construct platoons, in which vehicles have similar speed, headway, and the platoon state can be computed according to these states of vehicles in it. Similarly, the traffic state of one road segment can be calculated according to the states of platoons travelling on it. The road segments with the connected intersections having similar traffic state also can be divided into a subregion, in which similar traffic control strategy can be applied. From this view, the traffic network can be viewed as a hierarchical multigranularity model, in which the lower level traffic elements compose an upper level traffic element. However, these traffic elements cannot be represented by the common set concept, since there may be lower level elements that are not in an upper level set completely. That is, some lower level elements maybe belong to an upper level set partly. Furthermore, the state of traffic element changes in time; the dynamic of element state should be described in such model. Therefore, in this paper we try to model the traffic network as a hierarchical multigranularity model using the singular rough set theory in the following sections.

2.1. S-Rough Set Theory. According to the discussion in the previous section, there are four layers in the modeled traffic network, such as vehicle layer, platoon layer, segment and intersection layer, and subregion layer. Based on the rough set theory proposed by Professor Z. Pawlak in 1982 [17], these traffic elements can be represented using the upper and lower approximation set. The basic concepts of rough set theory are introduced as follows.

To the information system, there is a nonempty finite set of objects called universe \( U \). For \( X \subseteq U \), let \( R \) be an equivalence relation, and \( [x]_R \) denote the equivalence class of \( R \) defined by \( x \). Then, the approximation set of \( X \) is defined as

\[
\underline{R}(X) = \bigcup \{ x \mid x \in U, [x]_R \subseteq X \}
\]

\[
\overline{R}(X) = \bigcup \{ x \mid x \in U, [x]_R \cap X \neq \emptyset \}
\]

As shown in Figure 2, the area surrounded by black dotted line is the crisp set \( X \), the green blocks area is the lower approximation set of \( X \), and the grey together with green blocks area is the upper approximation set of \( X \). The upper and lower approximation sets of \( X \) can describe the rough
Figure 1: The dynamic of traffic elements in traffic network.

Figure 2: The rough representation of set $X$.

$\text{Boundary} (X) = \overline{R(X)} - R(X)$

Figure 3: The dynamic characteristics of S-rough set.

representation of the crisp set $X$. Boundary($X$) is the boundary of $X$ computed using the difference of the upper and lower approximation set. This rough representation is consistent with the realities in the world that objects may belong to a set partly. This kind of description can express the real world accurately.

However, the rough set defined above cannot describe the dynamic of $X$. That is, when the element state has been changed, the element may be transferred into or out of $X$. As shown in Figure 3, for $u_1 \notin X$, $u_2 \notin X$, $x_1 \in X$, $x_2 \in X$, there are some element operations $f(u)$ and $f'(x)$, which make $u_1$ become $f(u_1)$ with $f(u_1)$ belonging to $X$ completely, make $u_2$ become $f(u_2)$ with $f(u_2)$ entering $X$ partly, make $x_1$ become $f'(x_1)$ with $f'(x_1)$ not belonging to $X$ completely, and make $x_2$ become $f'(x_2)$ with $f'(x_2)$ leaving $X$ partly. This type of set $X$ with dynamic elements change cannot be described accurately using rough set theory. Therefore, the singular rough set theory (simplified as S-rough set) proposed by Professor Shi is introduced to solve this problem [18, 19], in
which the dynamic of set \( X \) is described using the elementary transfer operations.

Let \( F \cup F' \) be the elementary transfer on \( U \); there are \( F = \{ f_1, f_2, \ldots, f_m \} \) and \( F' = \{ f'_1, f'_2, \ldots, f'_m \} \). The effect of \( f \in F \) is defined as follows: for element \( u \in U \) and \( u \notin X \), there exists \( f(u) = x \), \( x \in X \). That is, \( f \) makes \( X \) occur with singularity. The existence of \( f \) makes the boundary of \( X \) extend outwards. Similarly, the effect of \( f' \in F' \) is defined as follows: for element \( x \in X \), there exists \( f'(x) = u \), \( u \notin X \). \( f' \) makes the boundary of \( X \) shrink inwards. The existence of both \( f \) and \( f' \) makes \( X \) occur with singularity in two directions, and \( X \) becomes \( X^\ast \); that is, \( X \) has two-direction dynamic character.

Let \( X^f \) denote the extension of \( X \), \( X'^f \) denote the shrink of \( X \), and the two-direction singular set \( X^\ast \) can be defined formally as follows.

\[
X^f = \{ u \mid u \in U, u \notin X, f(u) = x \in X \}
\]

\[
X'^f = \{ x \mid x \in X, f'(x) = u \notin X \}
\]

\[
X^\ast = X \setminus X^f \cap X'^f
\]

where \( f(u) \) is transferred into \( X \), and \( f'(u) \) is transferred out of \( X \) completely. According to the rough set definition, i.e., (1)-(2), the approximation of \( X^\ast \) can be described as

\[
(R, F \cup F')_+(X^\ast)
\]

\[
= \cup \{ x \mid [f(x)]_R \subseteq X^\ast \cup [x]_R \subseteq X^\ast \}
\]

\[
(R, F \cup F')^\ast(X^\ast)
\]

\[
= \cup \{ x \mid [f(x)]_R \cap X^\ast \neq \emptyset \cap [x]_R \cap X^\ast \neq \emptyset \}
\]

Therefore, the existence of \( F \cup F' \) makes \( X \) become \( X^\ast \); the dynamic characteristics of \( X \) with element transfer-in or transfer-out completely can be described using (6)-(7). In reality, there exist the cases of elements transfer partly. That is, for \( u \in U, u \notin X \), there is \( f(u) = x \) and \( x \) belongs to \( X \) partly (i.e., \( u \) is transferred into \( X \) partly); or for \( x \in X \), there is \( f'(x) = u \) and \( u \) belongs to \( X \) partly (i.e., \( x \) is transferred out of \( X \) partly).

For this case, the upper assistant set \( A^+(X^\ast) \) and the lower assistant set \( A^-(X^\ast) \) are defined as \( (8)-(9) \), where \( A^+(X^\ast) \) is made up of the elements transferred into \( X \) partly; \( A^-(X^\ast) \) is made up of the elements transferred out of \( X \) partly [20].

\[
A^+(X^\ast)
\]

\[
= \{ x \mid u \in U, u \notin X, f(u) = x, x \text{ enters } X \text{ partly} \}
\]

\[
A^-(X^\ast)
\]

\[
= \{ x \mid x \in X, f'(x) = u, u \text{ leaves } X \text{ partly} \}
\]

To sum up, the dynamic and the rough representation of \( X \) can be described using (6)-(9). According to the definitions of S-rough set, the elements in traffic network can be defined in similar ways. In the next section, these traffic elements in each layer are defined, respectively.

2.2 Traffic Granules Definition Based on S-Rough Set. Based on the discussion in previous sections, the traffic elements, such as vehicle, platoon, intersection and segments, and subregion, can be represented using S-rough set; their dynamic characteristics and rough representation can also be depicted.

As shown in Figure 4, there are four layers in the hierarchical multigranularity traffic network model. Vehicle is the smallest granule in this model. Vehicle granules with similar states form a platoon granule. There may be several platoon granules on a road segment. Segments with the connected intersections with similar traffic states construct a subregion, in which the intersection and segment is considered as a basic granule. The whole traffic network may be partitioned into several subregions. On the same layer, the lower level granules may be transferred from one upper level granule to another. For example, as shown in Figure 4, vehicle granules in platoon 1 may be transferred into platoon 2 when its states changed. Similarly, one intersection and segment granule may be transferred into or out of a subregion granule due to the changing traffic state of road segment. Furthermore, there exists the partly elementary transfer case: the vehicle at the head of a platoon will drive out from the platoon when it accelerates, and the vehicle at the end of a platoon will drive out from the platoon when it decelerates. In this case, the vehicle belongs to the platoon in position view while its acceleration is higher than the other vehicles; it can be said that the vehicle granule belongs to the platoon partly. There are the similar cases to the other granules. This is consistent with S-rough set definition. Therefore, using S-rough set to represent the granules in traffic network can describe the traffic network dynamic more accurately. In the following context, the singular rough representations of these traffic elements are listed except for the smallest vehicle granule.

(1) Platoon granule: Let these vehicles travelling on the same segment be the universe \( U_V \), \( R_P \) is the equivalence relation about the attributes of speed, acceleration, and position on \( U_V \). \( Plt \) denotes a platoon, \( Plt^\ast \) denotes the two-direction singular set of \( Plt \). \( F_V \cup F'_V \) is the elementary transfer, and there are \( F_V = \{ f_{V1}, f_{V2}, \ldots, f_{Vn} \} \) and \( F'_V = \{ f'_{V1}, f'_{V2}, \ldots, f'_{Vm} \} \), where \( f_V(veh) \) denotes that granule \( veh \) is transferred into \( Plt \) due to the changing of speed, position, and acceleration; \( f'_V(veh) \) denotes that granule \( veh \) is transferred out of \( Plt \) due to the changing of speed, position, and acceleration. Then, the singular rough set of a platoon is defined as

\[
Plt^\ast = Plt \setminus \{ veh \mid veh \in Plt, f'_V(veh) \notin Plt \}
\]

\[
\cup \{ veh \mid veh \in U_V, veh \notin Plt, f_V(veh) \in Plt \}
\]

\[
(R_P, F_V \cup F'_V)_+(Plt^\ast) = \cup \{ veh \mid [f_V(veh)]_{R_P} \subseteq Plt^\ast \}
\]

\[
\cup \{ veh \mid [veh]_{R_P} \subseteq Plt^\ast \}
\]
\[
\begin{align*}
\left( R_{p}, F_{v} \cup F'_{v} \right)^{+}(\text{Plt}^{*}) &= \cup \{ \text{veh} \mid [f_{v}(\text{veh})]_{R_{p}} \} \cap \text{Plt}^{*} \\
\circ & \not= \emptyset \wedge [\text{veh}]_{R_{p}} \cap \text{Plt}^{*} \not= \emptyset \\
A_{+}^{+}(\text{Plt}^{*}) &= \{ f_{v}(\text{veh}) \mid \text{veh} \in U_{v}, \text{veh} \} \notin \text{Plt} \text{ partly} \\
A_{-}^{+}(\text{Plt}^{*}) &= \{ \text{veh} \mid \text{veh} \} \notin \text{Plt} \text{ partly} \\
\in \text{Plt}, f'_{v}(\text{veh}) \text{ leaves Plt partly} \\
\end{align*}
\] 

\[\begin{align*}
\left( R_{seg}, F_{p} \cup F'_{p} \right)^{+}(\text{Seg}^{*}) &= \cup \{ \text{plt} \mid [f_{p}(\text{plt})]_{R_{seg}} \} \\
\circ & \not= \emptyset \wedge [\text{plt}]_{R_{seg}} \cap \text{Seg}^{*} \not= \emptyset \\
A_{+}^{+}(\text{Seg}^{*}) &= \{ f_{p}(\text{plt}) \mid \text{plt} \in U_{p}, \text{plt} \} \notin \text{Seg} \text{ partly} \\
A_{-}^{+}(\text{Seg}^{*}) &= \{ \text{plt} \mid \text{plt} \} \notin \text{Seg} \text{ partly} \\
\in S, f'_{p}(\text{plt}) \text{ leaves Seg partly} \\
\end{align*}\]

(2) **Segment granule:** Let these platoons travelling on the same segment be the universe \( U_{p} \). \( R_{seg} \) denotes the equivalence relation about the attributes of average speed and position on \( U_{p} \). \( seg \) denotes the segment with multiple platoons, and \( Seg^{*} \) denotes the two-direction singular set of \( Seg \). \( F_{p}(\text{plt}) \) is the elementary transfer on \( U_{p} \), where \( F_{p} = \{ f_{p1}, f_{p2}, \ldots, f_{pm} \} \) and \( f'_{p} = \{ f'_{p1}, f'_{p2}, \ldots, f'_{pm} \} \). \( f_{p}(\text{plt}) \) denotes that platoon \( \text{plt} \) is driving into \( Seg \), \( f'_{p}(\text{plt}) \) denotes that platoon \( \text{plt} \) is driving out of \( Seg \). Then, the singular rough set representation of segment is defined as

\[
Seg^{*} = Seg \setminus \{ \text{plt} \mid \text{plt} \in Seg, f'_{p}(\text{plt}) \notin \text{Seg} \} \\
\cup \{ \text{plt} \mid \text{plt} \in U_{p}, \text{plt} \notin \text{Seg}, f_{p}(\text{plt}) \in \text{Seg} \}
\]

\[
\left( R_{seg}, F_{p} \cup F'_{p} \right)^{+}(Seg^{*}) = \cup \{ \text{plt} \mid [f_{p}(\text{plt})]_{R_{seg}} \} \\
\circ & \not= \emptyset \wedge [\text{plt}]_{R_{seg}} \cap Seg^{*} \not= \emptyset \\
A_{+}^{+}(Seg^{*}) = \{ f_{p}(\text{plt}) \mid \text{plt} \in U_{p}, \text{plt} \} \notin Seg \text{ partly} \\
A_{-}^{+}(Seg^{*}) = \{ \text{plt} \mid \text{plt} \} \notin Seg \text{ partly} \\
\in S, f'_{p}(\text{plt}) \text{ leaves Seg partly} \\
\]

(3) **Subregion granule:** Since there are both segments and intersections in the subregion granule and the states of segments with the connected intersections affect the traffic control strategy, there are correlations between upstream and downstream segments; the “UpstreamSegment-Intersection-DownstreamSegment” (simplified as \( uid \)) is viewed as the basic granule in subregion granule definition. These \( uids \) compose the universe \( U_{r} \). Let \( SR \) denote a subregion, in
which the segments of uids have similar traffic state and there are correlations between the upstream and downstream segment of each uid. Since the uid is made up of upstream segment useg, downstream segment dseg, and the connected intersection intersec, if the useg and dseg are both transferred into or out of SR, it is to say that the uid is transferred into or out of SR completely. If only useg or dseg is transferred into or out of SR partly, let SR denote the two-direction singular set of SR, and $F_U \cup F^r_U$ is the elementary transfer on $U_5$, where $F_U = \{ f_U^1, f_U^2, \ldots, f_U^m \}$, $F^r_U = \{ f_U^{r1}, f_U^{r2}, \ldots, f_U^{rm} \}$. $f_U (uid)$ indicates that the basic granule uid is transferred into SR due to the state changing. $f_U^r (uid)$ indicates that uid is transferred out of SR due to the state changing. The rough representation of SR can be defined as

$$\text{SR}^* = \text{SR} \setminus \{ \text{uid} \mid \text{uid} \in \text{SR}, f_U (\text{uid}) \notin \text{SR} \} \cup \{ \text{uid} \mid \text{uid} \in U_5, \text{uid} \notin \text{SR}, f_U^r (\text{uid}) \in \text{SR} \}$$

(20)

$$R_{SR}, F_U \cup F^r_U \} (\text{SR}^*) = \{ \text{uid} \mid f_U (\text{uid}) \in \text{SR} \} \cup \{ \text{uid} \mid f_U^r (\text{uid}) \in \text{SR} \}$$

(21)

$$\cap \text{SR}^* \neq \emptyset \setminus \{ \text{uid} \} \cap \text{SR}^* \neq \emptyset \}$$

(22)

$$A^+ (\text{SR}^*) = \{ f_U (\text{uid}) \mid \text{uid} \in U_{SR}, \text{uid} \notin \text{SR}, f_U^r (\text{uid}) \} \setminus \text{enters SR partly}$$

(23)

$$A^- (\text{SR}^*) = \{ \text{uid} \mid \text{uid} \in \text{SR}, f_U^r (\text{uid}) \} \setminus \text{leaves SR partly}$$

(24)

2.3. Maintenance and Construction of Traffic Granules. Based on the definitions of the hierarchical multigranularity traffic network model, traffic control strategy can be designed aiming at different traffic demand to improve the efficiency of urban traffic control system. The key issue that this model can be utilized for traffic control and management is to maintain the integrity of these granules in real time. For the traffic data processing efficiently, the distributed traffic data management framework has been discussed in our previous research work [21]. In this section, it is assumed that the basic vehicle state information can be collected by the communication device equipped in vehicles and managed by the distributed traffic data centers.

For the granules in traffic network model, $U_V$, $U_P$, and $U_5$ are the vehicle universe, platoon universe, and segment universe, respectively. The smallest granule in this model is vehicle granule; the related attributes are listed as veh_id, veh_speed, veh_acc, veh_pos, segment_id, lane_id, preceding_id, following_id, pre_dist, back_dist, veh_class, passengers, veh_weight, etc. These attributes represent vehicle id, speed, acceleration, position, road segment id that vehicle travels on, lane id that vehicle travels on, the distance to the previous vehicle, the distance to the vehicle in back, vehicle class, the number of passengers in vehicle, and vehicle weight in mergerence, respectively. The attributes, such as veh_class, passengers, and veh_weight, can be utilized for light phase pressure computation in the traffic light control strategy design. In what follows, the constructions of three main traffic granules are listed in detail.

(1) Maintenance and construction of platoon granule: The equivalence relation $R_p$ on $U_V$ is used for constructing a platoon on each road segment; it is defined as follows: vehicles with neighboring position and same segment_id, same lane_id, similar speed and acceleration. The elementary transfer is defined as follows: For veh $\notin p$, if $\text{Minspeed}_{platoon} \leq \text{veh.speed} \leq \text{Maxspeed}_{platoon}$, $|\text{veh.acc}| \leq \text{acc_threshold}$, pre_dist $\leq \text{dist.threshold}_p$, or back_dist $\leq \text{dist.threshold}_p$, then veh is transferred into platoon $p$ completely; if $\text{pre_dist} > \text{dist.threshold}$ and $\text{veh.acc} < \text{acc_threshold}$ or $\text{back_dist} > \text{dist.threshold}$ and $\text{veh.acc} < \text{acc_threshold}$, then veh is driving into platoon $p$, since veh is accelerating from the back of $p$ or decelerating in front of $p$; after a period of time veh will drive into platoon $p$. In this case, it is said that veh is transferred into $p$ partly. For veh $\in p$, if there is $|\text{veh.acc}| > \text{acc_threshold}$, veh in $p$ is accelerating or decelerating; after a period of time, veh will leave platoon $p$. In this case, it is said that veh is transferred out of $p$ partly. If veh is the head or rear of $p$, when $\text{back_dist} > \text{dist.threshold}$ or $\text{pre_dist} > \text{dist.threshold}$, it is said that veh has been transferred out of $p$ completely.

(2) Maintenance and construction of road segment: For the universe $U_P$, the basic granule is platoon, the related attributes including platoon_id, ave_speed, max_speed, min_speed, ave_headway, max_headway, min_headway, veh_count, seg_id, lane_id, platoon_weight, rightofway_flag, etc. These attributes represent the vehicle id, average speed, maximum speed of platoon, minimum speed of platoon, average headway, maximum headway, minimum headway, number of vehicles in platoon, segment id that the platoon is travelling on, lane id, the weight of platoon, and whether the platoon obtains the right of way to pass the downstream intersection, respectively. The equivalence relation $R_s$ on $U_P$ is defined as follows: platoons with same segment_id and lane_id. The elementary transfer of platoon granule on segment granule is defined as follows: For $p \in s$, if rightofway_flag is true and $\text{veh_count} < \text{veh_count}_{\text{threshold}}$, it is said that platoon $p$ can pass through the downstream intersection in green time; then $p$ is transferred out of segment $s$ completely; if rightofway_flag is true and $\text{veh_count} > \text{veh_count}_{\text{threshold}}$, it is said that part of platoon $p$ will pass through the downstream intersection in green time; then $p$ is transferred out of segment $s$ partly. For $p \notin s$, there are similar situations.

(3) Maintenance and construction of subregion granule: For constructing the subregion granule, uid is the basic granule, which constitutes the universe $U_V$. The related attributes include uid_id, upseg_state, downseg_state, and correlation_degree, representing uid id, state of upstream segment, state of downstream segment, and correlation degree of the upstream and downstream segments, respectively. The state of segment can be extracted from platoon granules on it using the attributes seg_id, veh_count, ave_speed, queue_length, and seg_cap, where seg_cap is the capacity of a road segment. The correlation degree can be calculated according to the state
and capacity of upstream and downstream segments [22]. The equivalence relation $R_{SR}$ on $U_{SR}$ is defined as follows: segments have similar state and the correlation degree is more than a given threshold. The elementary transfer is defined as follows: For $uid \in SR$, if the number of vehicles and the average speed of upstream and downstream segments are both exceeding the given range of subregion $SR$, that is, the upstream and downstream segment states of $uid$ are not close to the state of $SR$, it is said that $uid$ is transferred out of $SR$ completely. If only the downstream or upstream segment state is not close to the state of $SR$, it is said that $uid$ is transferred out of $SR$ partly. For $uid \notin SR$, if $uid$ is adjacent with $SR$ and the upstream and downstream segment states of $uid$ are similar to the state of $SR$, it is said that $uid$ is transferred into $SR$ completely. If only upstream or downstream segment state is similar to the $SR$ state, it is said that $uid$ is transferred into $SR$ partly.

Based on the construction and maintenance of granules in the proposed traffic network model discussed above, these traffic granules can be maintained in a distributed mode under a distributed traffic data management framework. Then, the traffic information of different layers and granularities can be extracted. Based on the multigranularity traffic information, including vehicle information, platoon information, segment information, and subregion information, the traffic control and management system may adopt more suitable strategies to improve the efficiency. However, still some issues have not been presented in detail in this proposed model, such as the parameters selection of traffic state, traffic state computation of road segment, and the correlation degree calculation between downstream and upstream road segments. These problems will be researched in further work. In this paper, to illustrate the validity and feasibility of the proposed hierarchical multigranularity traffic network model, we propose a max-pressure based traffic control strategy in the next section.

3. Traffic Control Strategy Based on the Proposed Traffic Model

In this section an application based on the proposed traffic network model is discussed. The proposed traffic network model is combined with the max-pressure traffic control algorithm to design an extended max-pressure traffic control strategy, in which the light phase pressure is computed using the rough representations of platoon and segment granules.

3.1. Max-Pressure Traffic Control Strategy. The max-pressure traffic control strategy is proposed by Varaiya [23] based on the backpressure traffic control algorithm [24, 25]. According to the strategy, the urban traffic network is viewed as a queuing network, and at each time slot the active phase of each intersection is selected depending on the light phase pressure computed using local queue length of each connected road segment.

As shown in Figure 5, on segments $a$ and $g$, there are queued vehicles waiting for passing through intersection $i$; the vehicle flows $f_{ab}$ and $f_{gh}$ are controlled by light phase $p$ of intersection $i$. For the vehicle flow $f_{ab}$, when it enters the downstream segment $b$, it will drive into the queued vehicles $q_{bc}$ and $q_{bc}''$ according to the proportions $r_{bc}$ and $r_{bc}''$, where $c'$ and $c''$ are the downstream segments of $b$. There are similar situations for the vehicle flow $f_{gh}$. The pressure of light phase $p$ of intersection $i$ is computed using (25), and the active light phase in next time slot is selected using (26).

$$\text{pressure}_p = \sum_{f_{ab} \in p} \mu_{ab}(p) \left( q_{ab}(t) - \sum_c r_{bc} q_{bc}(t) \right)$$  \hspace{1cm} (25)$$

where $f_{ab} \in p$ means that the vehicle flow $f_{ab}$ is controlled by light phase $p$; $\mu_{ab}(p)$ is the number of vehicles passing through intersection per unit time when $p$ is activated.

$$p^* = \arg \max_{p \in P_i} \left( \text{pressure}_p(t) \right)$$ \hspace{1cm} (26)$$

where $p \in P_i$ means that $p$ is one of the light phases of light signal group $P_i$.

In this method, the light phase pressure is concerned with the number of queued vehicles in front of the stop line on the upstream and downstream segments. The detailed vehicle information, the arriving vehicles (for the upstream segment), and the departing vehicles (for the downstream segment) are not considered. Based on the proposed traffic network model, there may be several platoons with different states on the upstream and downstream segments. On the upstream segment, there are stopped platoons in front of the stop line and arriving platoons heading for the stop line. On the downstream segment, there may be the departing platoon when the corresponding downstream light phase is activated. These situations are considered in the traffic network rough representation discussed in previous sections. Therefore, in the next section, the light phase pressure computation method is extended based on the proposed hierarchical multigranularity traffic network model.

3.2. Extended Max-Pressure Traffic Control Algorithm. Actually, the light phase pressure is affected by four types of...
platoons on the segment. For the platoons on upstream segment, the stopped platoons waiting for passing through the intersection, the platoons that are driving towards the stop line, and the platoons on the neighboring lanes that are going to drive into the corresponding lanes will affect the light phase pressure. For the platoons on downstream segment, the departing platoon affects the light phase pressure computation too, if the downstream light phase is activated. Since the rough representation of traffic granules includes detailed traffic information, the vehicle weight, the number of passengers, vehicle class, etc. also can be considered. Then, based on the rough representation of platoon and segment in the proposed traffic network model, the light phase pressure can be computed more accurately.

To simplify the description, the rough set representation of $X^*$ with elementary transfer in two directions is denoted by the lower approximation set \(\text{appr}_{<}(X^*, F \cup F')\) and the upper approximation set \(\text{appr}_{>}(X^*, F \cup F')\). \(\text{appr}_{<}(X^*, F)\) represents the one-direction lower approximation set with element transfer-in operations, and \(\text{appr}_{>}(X^*, F)\) represents the one-direction lower approximation set with element transfer-out operations. The upper assistant set \(A^*_{>}(X^*, F)\) represents the set that elements enter $X^*$ partly under transfer operations $F$. The lower assistant set \(A^*_{<}(X^*, F')\) represents the set that elements leave $X^*$ partly under transfer operations $F'$. Then, the pressure from each platoon can be computed using

$$
\text{pressure}_{plt} \left( P_{\text{seg}}^*, t \right) = \sum_{\text{veh} \in \text{appr}_{<}\left( P_{\text{seg}}^*, F \cup F' \right)} \alpha \omega_{\text{veh}} + \sum_{\text{veh} \in A^*_{<} \left( P_{\text{seg}}^*, F \cup F' \right)} \beta \omega_{\text{veh}}
$$

(27)

where $\alpha$, $\beta$ is the coefficient of the vehicle weight and $\omega_{\text{veh}}$ is the vehicle weight determined by the vehicle type; it means that the different types of vehicles generate different pressure due to the different number of passengers and emergence of these vehicles.

The pressure of the upstream segment is computed using

$$
\text{pressure}_{\text{useg}} \left( \text{seg}_{\text{seg}}^*, t \right) = \sum_{\text{plt} \in \text{appr}_{>}(\text{seg}_{\text{seg}}^*, F \cup F')} \text{pressure}_{\text{plt}} \left( P_{\text{seg}}^*, t \right)
$$

(28)

where useg represents an upstream segment and seg$_{\text{seg}}$ is a subsegment on segment a, in which platoons on segment a are waiting for driving into segment b.

The pressure of the downstream segment is computed using

$$
\text{pressure}_{\text{dseg}} \left( \text{seg}_{\text{seg}}^*, t \right) = \sum_{c \in \{ c' \cup c'' \} \setminus \text{appr}_{>}(\text{seg}_{\text{seg}}^*, F \cup F')} \text{pressure}_{\text{plt}} \left( P_{\text{seg}}^*, t \right)
$$

(29)

According to (28), (29), the vehicles entering upstream segment and departing from downstream segment are considered for the coordination with neighboring intersections.

The pressure of light phase $p^i_j$ is computed using

$$
\text{pressure}_{\text{phase}} \left( p^i_j, t \right) = \sum_{\text{seg}_{\text{seg}} \in \text{seg}_{\text{seg}}^*} \left( \text{pressure}_{\text{useg}} \left( \text{seg}_{\text{seg}}^*, t \right) - \text{pressure}_{\text{dseg}} \left( \text{seg}_{\text{seg}}^*, t \right) \right) \mu_{ab} (t)
$$

(30)

where $p^i_j$ is the $j$th light phase of intersection $i$; $p^{i+1}_j$ is the cooperative light phase of the downstream intersection $i+1$.

Based on the extended pressure computation method described above, the vehicle type, vehicle state and platoon state, upstream light phase state, and downstream light phase state are considered. If the element transfer operations $F$ and $F'$ are both empty, the extended pressure computation method degenerates into max-pressure traffic control algorithm. If $F_P \neq \Phi$ and $F'_P \neq \Phi$, the arriving vehicles from upstream segment are considered in the pressure computation; in this case the coordination with the upstream intersection light phase can be achieved. If $F_P = \Phi$ and $F'_P = \Phi$, the departing vehicles on the downstream segment are considered to achieve the coordination with downstream intersection light phase. The light phase with max-pressure is selected to be activated in the next time slot using (26).

Furthermore, the vehicle class, the number of passengers, and vehicle emergency also can be considered using the vehicle weight. Therefore, based on the extended light phase computation method, the real situations of traffic control system can be reflected. The strategy may be more suitable for the actual situation of urban traffic network. To illustrate the effectiveness and feasibility of the proposed model and algorithm, simulations are carried out in the next section.

4. Simulations

In this section, the simulation is carried out to analyze the effectiveness and feasibility of the proposed method. The simulation traffic network consists of 15 intersections and 76 links constructed in Vissim. The network includes 16 ingress segments and 16 exit segments, as shown in Figure 6(a).

The vehicle input of each ingress link is 800 veh/h. There are 15 signal controllers and 4 light phases for each controller, i.e., north-south straight phase, north-south left-turn phase, west-east straight phase, and west-east left-turn phase. There are 3 lanes on each link. The left-turn vehicle flow drives on Lane 3 and the straight vehicle flow drives on Lane 2. The two vehicle flows are controlled by the traffic light. The right-turn vehicle flow drives on Lane 1 and is free of the traffic light. To obtain the traffic parameters during simulation, 60 queue counters, 60 travel time sections, and 60 routing decisions are laid on the simulation traffic network, as shown in Figures 6(b), 6(c), and 6(d). During the simulation, the green light time of each light phase is assumed to be 21 s, which is the pedestrian clearance time (the road width is about 21 m, and the pedestrians speed is about 1 m/s) [26]. The yellow light time is assumed to be 3 s.
To illustrate the efficiency and feasibility of the proposed traffic network model and traffic control algorithm, three traffic light control methods are implemented in this section, including fixed-time control (FT method), max-pressure control (MP method), and the extended max-pressure control (EMP method). To simplify the simulation, the extended pressure computation only considers the case of $F_p = \Phi$ and $F'_p \neq \Phi$ in this paper; the other cases will be considered in further research works. The three traffic light control methods are implemented in Visual Studio 2010. The simulation programs communicate with Vissim through the Vissim COM programming interface to obtain the vehicle state and traffic parameters, to decide the traffic light signal at each time slot. The simulation runs for 3,600 s, and the traffic network performance is evaluated from 1,000 s to 3,600 s using Vissim. This is because in the first 1,000 s of simulation time there are not enough vehicles entering the simulation traffic network.

The simulation results of the traffic network are listed in Table 1. According to the simulation results, EMP method based on the proposed hierarchical multigranularity traffic network model achieves better performance, because the light phase pressure computed using (27)-(30) is closer to the actual traffic situation, in which the vehicles on a road segment are represented using rough set form. The departing vehicles of downstream segments considered in this simulation can achieve the coordination with downstream intersections.

As shown in Figure 7, the average queue length under EMP method is shorter than the other traffic light control methods. The shorter queue length in traffic network means it can effectively reduce the occurrence of spill-over on downstream road segment, so as to avoid the traffic collapse due to vehicle queue overflow. EMP method is based on the proposed hierarchical multigranularity traffic network model, in which the traffic elements dynamic characteristics are depicted accurately, and the light phase states of downstream intersections are also considered to compute the light phase pressure; therefore, EMP method achieves better performance. As shown in Figure 8, the average travel time under EMP control is lower than the other two methods.

Furthermore, using the extended pressure computation method based on the proposed traffic network the priority

<table>
<thead>
<tr>
<th>Parameters</th>
<th>FT Method</th>
<th>MP Method</th>
<th>EMP Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total travel time (h)</td>
<td>633.947</td>
<td>588.139</td>
<td>568.009</td>
</tr>
<tr>
<td>Total delay time (h)</td>
<td>350.255</td>
<td>298.110</td>
<td>277.457</td>
</tr>
<tr>
<td>Total stopped delay (h)</td>
<td>253.507</td>
<td>225.692</td>
<td>205.465</td>
</tr>
<tr>
<td>Average delay time (s)</td>
<td>130.584</td>
<td>111.420</td>
<td>104.057</td>
</tr>
<tr>
<td>Average stopped delay (s)</td>
<td>94.514</td>
<td>84.353</td>
<td>77.057</td>
</tr>
<tr>
<td>Average speed (km/h)</td>
<td>23.527</td>
<td>25.916</td>
<td>26.883</td>
</tr>
<tr>
<td>Number of vehicles in network</td>
<td>448</td>
<td>368</td>
<td>334</td>
</tr>
<tr>
<td>Number of vehicles that left network</td>
<td>9208</td>
<td>9264</td>
<td>9265</td>
</tr>
<tr>
<td>Total Number of vehicles</td>
<td>9656</td>
<td>9632</td>
<td>9599</td>
</tr>
</tbody>
</table>
control for some particular vehicles can be achieved conveniently, since different classes of vehicles can be set with different vehicle weight in the EMP method. Different weight values can result in different traffic efficiency for different types of vehicles. For example, when the type of bus is added to the simulation traffic network, the higher weight value can make buses have higher average speed, and the other classes of vehicles maybe achieve lower average speed. For this issue, the vehicle weight selection is important. As shown in Figure 9, the different bus weight values are simulated, and they result in different average speed. According to the multiple simulation results and the real traffic demand, the vehicle weight can be determined.

To sum up, since the hierarchical multigranularity traffic model can represent the actual traffic network situations accurately and the EMP method can achieve traffic control flexibly, this paper may be a useful attempt in solving urban traffic control problem.

5. Conclusions

In this paper, a hierarchical multigranularity traffic network is proposed, and on the basis of the proposed traffic network an extended max-pressure traffic control method is implemented. The simulation results illustrate that the proposed traffic network model and EMP method achieve better performance. In the proposed model the traffic elements in urban traffic network are represented using S-rough set, in which the dynamic characteristics of traffic elements are depicted. This type of traffic element description can represent the traffic network situation accurately, so as to design the more efficient traffic control strategy.

However, the hierarchical multigranularity traffic network model is only a preliminary exploration, and it needs to be further improved in the future research work, such as the traffic subregion formulation and the boundary control of traffic subregion. For the traffic subregion formulation, the correlation of downstream and upstream road segments should be computed considering traffic states and the geographical characteristics of each pair of upstream and downstream segments. The control strategy of subregion boundary can compute the traffic pressure considering the remaining capacity of downstream segment to speed up the vehicle flow release towards to the segment with larger remaining capacity. These issues will be studied in our further research work to improve the hierarchical multigranularity traffic network model. Furthermore, in the future work, the completely multigranularity traffic control strategies should be further researched using granular computing theory to achieve the traffic system multigranularity control completely.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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Figure 7: Average queue length of the three-traffic-light control method.

Figure 8: Average travel time of the three-traffic-light control method.

Figure 9: Simulation results with different bus weight values.
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References


