Research on Modeling and Simulation for Railway Transportation System

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Abstract: This paper studies the modeling theories and simulation methods for railway transportation system. The railway transportation system is a typical temporal-spatial dynamic system. Recently the method with temporal-spatial computation characteristics, Cellular Automata, is often used for road traffic flow research, but it's homogeneity restricting make it impossible to modeling railway transportation system, for the objects can not be divided into cells with same size and same transformation rule in railway transportation system. Based on the research on railway transportation system's characteristics and Cellular Automata Theory, the Entity Automata model is put forward. Entity Automata divided the objects in railway transportation system into several classes and every class entity has it own characteristics and transformation rule. It inherits the temporal-spatial computation characteristics of Cellular Automata and integrates object-oriented method. Simulation experiment result shows using Entity Automata to model and simulate railway transportation system is feasible.

Key words: Entity Automata, temporal-spatial model, railway transportation system

1. INTRODUCTION

Railway transportation system has been studied for a long time to increase transportation efficiency. Railway transportation system is made of immovable stations, tracks, sections, block subsections, signals and movable trains, these entities' states always transfer with time, so railway transportation system is a dynamic system. But differing from other dynamic systems, almost all objects in railway transportation system have spatial properties, and states' transformation of object in this system is influenced by the states of their spatial neighbouring objects, and system states transformation is discrete. From railway transportation system's dynamic characteristics, spatial properties and spatial interaction, it is a typical discrete temporal-spatial dynamic system.

For this typical discrete temporal-spatial dynamic system, the existing modeling and simulation method used to analyze system's state transformation only according to temporal dimension but ignore the influence of spatial factors and the spatial interaction among elements in system. So a modeling and simulation method that both time factors and spatial factors are taken into account during system modeling processes should be developed to describe spatial-temporal transformation process of railway transportation system.

2.ENTITY AUTOMATA MODEL

The term "Cellular Automata (CA)" comes from defining discrete squares of space, or cells, and each cell has a set of rules that governs its state at each time step automatically. In CA, the state of a cell at a given time depends on its own state one previous time step and the state of its nearby neighbors at the previous time step (Wolfram, 1986). For CA have temporal-spatial computation characteristics, many Cellular Automata models of road traffic have been developed (Nagel, K. *et al.* (1992), Gould (2000), Hattori *et al.* (1999), Chrobok, R. *et al.* (2001)) But there are a lot of difference between road and railway that make it impossible to put Cellular Automate into railway transportation system modeling:

- The research object in road transportation system is traffic flow, not a vehicle, cell can be either empty or occupied by at most one vehicle at a given instant of time. In railway transportation system train's state is also a research emphasis and train keeps moving all time.
- Cell size is same and every cell's state transform according to the same transformation rules in Cellular Automata and Cellular Automata models of road traffic while the space size of basic unit is different and different kind of unit has different transformation rule in railway transportation system.
- In cellular automata model, cell cannot be divided into smaller cell while in railway transportation system not only the basic unit's state need to be described but also some entities' states in this basic unit need to be described. For example, a station's state need describing, tracks' states in it is also need researching.

Though Cellular Automata has temporal-spatial computation characteristics, it's homogeneity restricting make it impossible to modeling railway transportation system. This paper put forward Entity Automata (Wang, 2002) that inherits the temporal-spatial computation characteristics of CA and integrates object-oriented method. It can describe railway transportation system which contain movable entities and breaks Cellular Automata's homogeneity restricting. It keeps cellular automata's spatial-temporal computation character, but expand its adaptability to the systems with complicated structure and complicated state transformation rules.

(1) Define of Entity Automata

Entity Automata model is made of Entities, limited States, Neighborhood, Rules and spatial Properties of movable entities, can be defined:

$$EA=(ES, N, S, P, f) \quad (1)$$

In expression (1), *EA* denotes Entity Automata, *ES* denotes entity space, *N* denotes entity neighborhood, *S* denotes the set of entity, *P* denotes spatial properties of movable entities and *f* denotes entity local state transformation rule.

- **Entity**: In Entity Automata model, object that has whole state transformation is defined as entity. It can be basic unit that cannot be divided further and can be object that contains other basic unit in it.
- **Relation**: The spatial relative position among entities. Relation can be divided into neighborhood relation (when two entities joint each other) and containing relation (when an entity contains another entity in it)
- **State** and **State Set**: Entity only has one state at a given time, and this state belongs to a set that has limited number elements, this set is state set. For railway transportation system, entities' state and state set can be expressed as following.

For semi-automatic block section and track in station:

$$S=\{idle, occupied\} \quad (2)$$

For automatic block

$$S=\{idle, slowdown, stopping, occupied\} \quad (3)$$

For station:

$$S=\{ready\ for\ receiving\ train, receiving\ train, dispatching, \ldots\ldots\} \quad (4)$$

For train:

$$S=\{stopping, moving\ at\ speed\ v_1, moving\ at\ speed\ v_2, \ldots\ldots, moving\ at\ speed\ v_l\} \quad (5)$$

- **Entity Space**: All entities in a given researching area make an entity space.
- **Neighborhood**: entities that have neighborhood relation with center entity, entities that have containing relation with center entity or center entity's neighbor are both called neighborhood of the center entity.
- **Rule**: functions and language rules that elucidate entity state transformation rule are defined as rule.
- **Spatial Position** of movable entities: In railway transportation system, spatial position of movable entities (train) is function of time, can be described as follow:

$$P=fp(t) \quad (6)$$

Cells in cellular automata are immovable, but some entities in railway transportation system are movable, for example, train, and some entities are immovable, such as railway line, station, etc. The position of movable entities vary with time change and just this position' variability trigger the discrete event occur and entities' state transformation. So the spatial position of movable entities must be described specially.

(2) Object-Oriented Entity Automata
Object-Oriented theories adopt down-top process and parallel method and have the same basic principle as cellular automata's model mode. So in this paper, Entity Automata integrates object-oriented method and all entities are divided into some entity object classes.

- Immovable entity class: entities that positions do not change.
- Movable entity class: entities positions vary when time change, such as train class.
- Immovable entity class can be divided into several subclasses: station class, section class, track class and automatic block class.

After classing the entities in railway transportation system, for an entity *i* that belong to class *m*, its state transformation can be describe as equation (7)

$$s_i(t+\Delta t)=f_m(s_i(t), N_i(t), p_i(t), \Delta t) \qquad (7)$$

Where, $s_i(t+\Delta t)$ is the state of center entity *i* that belong to class *m* at time $t+\Delta t$; $s_i(t)$ is the state of center entity *i* at time *t* (class *m*); f_m is local state transformation rules of class *m*; $N_i(t)$ is state set of center entity *i*'s neighborhood at time *t*; $p_i(t)$ is positions of movable entities in center entity *i*'s neighborhood and Δt is time step.

Equation (7) is a similar Entity Automata frame model as cellular automata, railway transportation system model can be formulated using it.

3. ENTITY AUTOMATA MODELFOR RAILWAY TRANSPORTATION SYSTEM

As equation (7) shows, when we describe railway transportation system's state transformation, local state transformation rules, neighborhoods of entity and positions of movable entity must be ascertained firstly.

(1) Entity State Transformation Rules
Though not every entity has same state transformation rule, after dividing these entities into several classes, each class entities will have same local rule. For railway transportation system with certain operation mode and management rule, every local state transformation rules have made certain.

(2) Movable Entities' State and Spatial Position
Some simplifications are made during modeling process in order to reduce computation time. For example, the length of train is ignored, that is, the train is regarded as a particle. Train's state set can be described as equation (5):

$$S_{train}=\{0, v_1, v_2, \ldots\ldots, v_l\} \qquad (8)$$

At a given time *t*, for any train entity, its state $s_i(t)=v_i\in S_{train}$, its spatial position is sole and as equation (6)

$$p_i(t)=f_p(t).$$

Where, *k* is the number of all train entities in the system.

(3) Entity Neighborhood
When class train entities' positions have given, the relation between train entity and immovable entities, the relation between train entity and other train entities have settled. According to entity's definition, entity's neighborhoods have settled. So, all entities' neighborhoods at time *t* have decided, denotes as $N(t)$.

(4) Descriptions of System Dynamic Process
At time *t*, if any entity *i*'s state is $s_i(t)$, all entities' states can be expressed as:

$$S(t)=(s_i(t) \mid i=1, 2, \ldots\ldots, n) \qquad (9)$$

Where, *n* is the number of all entities in the system.
According to equation (9), movable class entities (trains) can be expressed as equation (10):

$$P(t)= (p_1(t), p_2(t), \ldots\ldots, p_k(t)) \qquad (10)$$

Where, *k* is the number of all movable entities.
When systems S(t), P(t) is given, that is all entities' states and movable entities' positions have given, the whole states of system (all entities' states and movable entities' positions) can be made out, describe as:

$$System(t)=(S(t), P(t)) \qquad (11)$$

When system time advances from t to $t+\Delta t$, from equation (7), $s_i(t+\Delta t)=f_m(si(t), N_i(t), p_i(t), \Delta t)$, all entities' states at time $t+\Delta t$ can be work out, so all entities' states can be described as following:

$$S(t+\Delta t)=\{s_i(t+\Delta t)|\ i=1,2,\ldots\ldots,n\} \qquad (12)$$

At this time, for any train entity i, its displacement Δs in time Δt is:

$$\Delta s= v_i*\Delta t \qquad (13)$$

When railway net and trains moving route have given, for any train i, its spatial position $p_i(t+\Delta t)$ at time $t+\Delta t$ can be work out from its spatial position at time t $p_i(t)$, its displacement Δs in time Δt, and described as

$$p_i(t+\Delta t)=fun\ (p_i(t),\ s_i(t),\ \Delta t)) \qquad (14)$$

All train entities' position set is

$$P(t+\Delta t)=(p_1(t+\Delta t),p_2(t+\Delta t),\ldots\ldots,\ p_k(t+\Delta t)) \qquad (15)$$

So System(t+Δt) can be described as equation (17)

$$System(t+\Delta t)=(S(t+\Delta t),\ P(t+\Delta t)) \qquad (16)$$

At time $t+\Delta t$, when class train entity's spatial position has been work out, the relation between this train entity and immovable entities, the relation between it and other train entities have settled, so its neighborhood can be work out, denotes as $N_i(t+\Delta t)$. So, the whole state of system at next time step can be work out according to equation (7) and (12)-(16).

When all entities in railway transportation system have been divided into several classes, entities' state transformation rule will be same for entities belong to same class. After all entities' state transformations have work out according their transformation rules of its class, the state of whole system transformation will have done.

For a railway transportation system with m classes, n entities and k movable entities, its dynamic process can be shown as figure 1

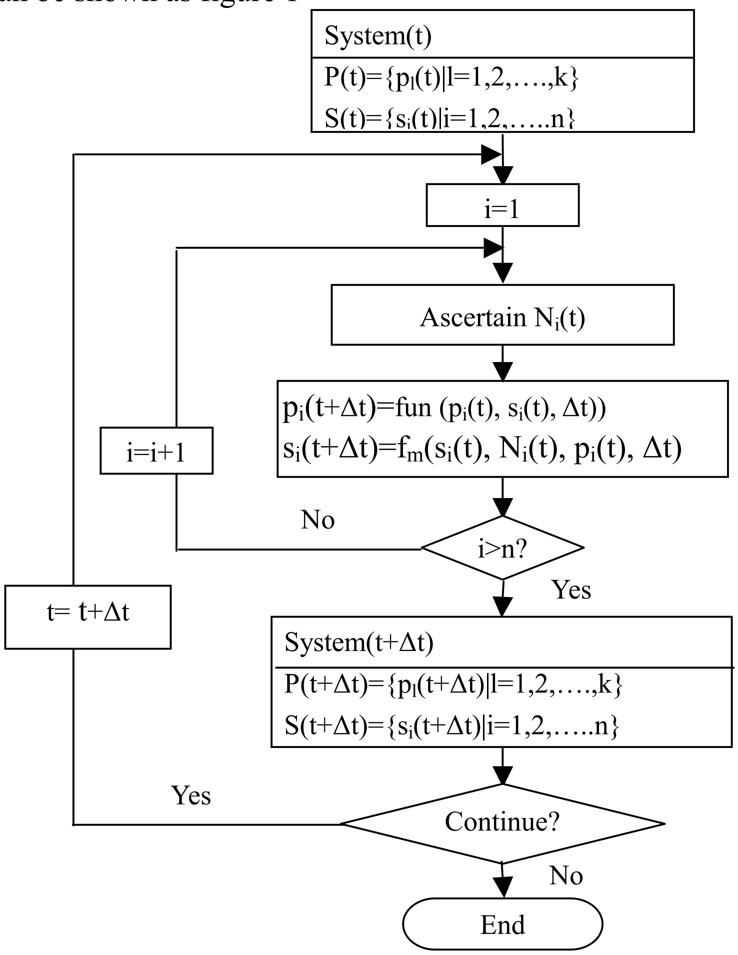

Figure 1. System State Transformation Process in Entity Automata Model

4. SIMULATION PLATFORM AND SIMULATION EXPERIMENT

(1) Existing Methods for Train Operation Simulation

Since it is impossible to make train operation actual experiment, computer simulation technologies and methods have been used to evaluate train operation scheme and dispatching strategies for a long time (Cheng *et al* (1994), Kataoka *et al* (2000), Okumura *et al* (2000), Fernandez *et al* (1994), Ello *et al* (1998)). Discrete Event Dynamic System simulation technologies often to be used to simulate train operation for it is difficult to find an equation set to describe trains' behaviors exactly. The common methods of train operation simulation are event-driven simulation and network-based simulation like Petri Net methods.

Because logic and restricted relations of events is not easy to be recognized clearly, event-driven simulation method will take a lot of time to find an event's conflicting objects. And Conflict detecting and solving is very complicated. When an event happening is not only related to time but also related to other conditions, for example, related with spatial state in train operation simulation process, the event-driven simulation will reveal its weak point. Network-based simulation is more faster then event-driven simulation, but the logic sequence of simulation solving is determined by topological sequence in advanced and can not be changed during simulation process. Furthermore, both event-driven simulation and network-based simulation are regardless of objects' spatial relation in railway transportation system and while states' transformation of object in railway transportation system is influenced by the states of their spatial neighbouring objects.

(2) Entity Automata Simulation

Entity Automata is a temporal-spatial dynamic frame model that is suit for railway transportation system simulation, it is easy to describe spatial-temporal transformation process of railway transportation system. From figure 1, when we build a simulation software platform for railway transportation system using Entity Automata frame model, entities' relations (used to ascertain entities' neighborhoods) and state transformation rules must be research.

■ Entities' Relations and Neighborhood

Only entities' relations have been ascertained that the entities' neighborhood could be ascertained when modeling a railway transportation system using Entity Automata frame model. Following is just an example to show entity relations in railway transportation system.

- Relation between train and station.
  Relation name: up-heading-for /up-approaching
  Type of relation: one-to-one.
  Relation: up-heading-for (train to station).
  Inverse of relation: up-approaching (station to train).
  Description: a train may be up-heading-for at most one station;
  a station may be up-approaching at most one train.
  Meaning: dynamic relation between train running in section and its forward station.
  Derive from neighborhood relation.

■ Entity State Transformation Rules

For a railway transportation system modeling, if we want to describe system state transformation using Entity Automata model, entity local state transformation rules must be known. Some rules can be express as function, others is language rules, that is, the state transfer of a system is driven by events, but the events happening must have its certain conditions and rules. In our simulation system, using expert system technology, a knowledge base is set up for representing these nonquantitative, nonstructural rules and conditions. The following is just an example of these language rules.

- Rule for train departure at a station:
  For any train ATrain that is hold-by any station AStation if (the status of ATrain is dwelling and the departure-time of ATrain <= the time-counter of system-timer) or the status of ATrain is passing then start dispatch-a-train.

■ Simulation Results

Using Entity Automata frame model, a simulation platform for railway transportation system is set up. Based on this simulation platform, simulation experiment for Guangzhou-Shenzhen railway organization of train operation has been done. This simulation platform can imitate the actual operation of Guangzhou-Shenzhen railway. The simulation experiments about different strategies of operation, dispatch and groundwork building can be done with this simulation software. Figure 2 is the main display picture of simulation process and figure 3 is the actual train operation diagram about simulation process.

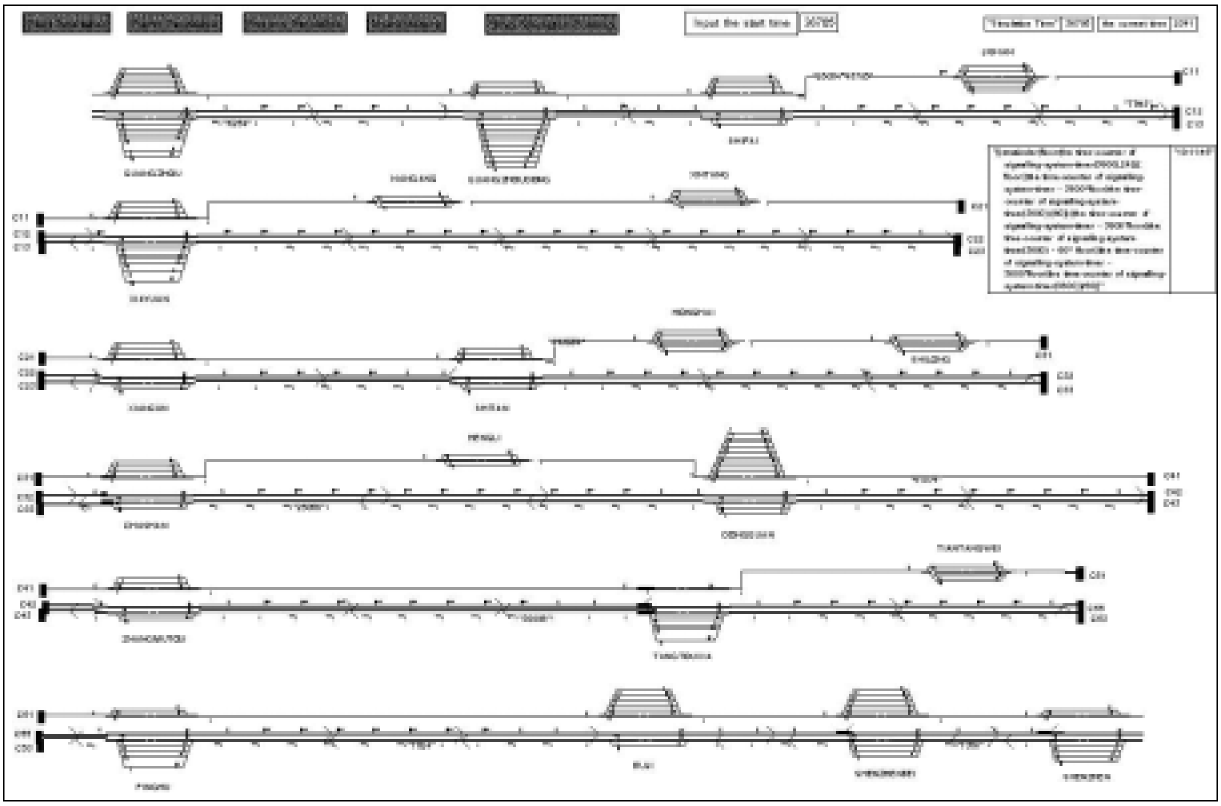

Figure 2. System Main Display Picture

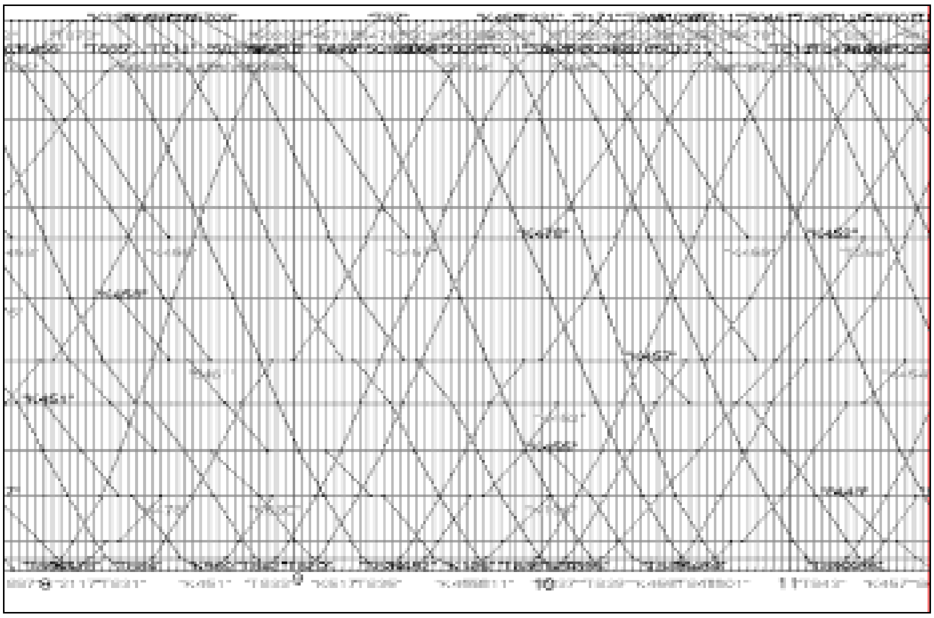

Figure 3. Railway Train Operation Diagram (Part)

5. CONCLUSION

This paper studies the modeling theories and simulation methods for railway transportation system. The railway transportation system's characteristics are analyzed in this paper and the analysis shows that railway transportation system is a typical temporal-spatial dynamic system. Based on the research on railway transportation system's characteristics and Cellular Automata Theory, the Entity Automata model is put forward. Entity Automata divided the objects in railway transportation system into several classes and every class entity has it own characteristics and transformation rule. It inherits the temporal-spatial computational characteristics of Cellular Automata and integrates object-oriented method. Simulation experiment is done on the railway transportation system simulation software platform that built using Entity Automata frame model. Simulation experiment process and results show using Entity Automata to model and simulate railway transportation system is feasible.

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