A HIGHWAY VARIABLE SPEED LIMIT CONTROL SYSTEM BASED ON INTERNET OF THINGS

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ABSTRACT

It is an important issue of Intelligent Transportation System, how to quickly relieve the highway congestion. The variable speed limit control system can limit the traffic flow before the highway congestion zone. So it is wildly used to relieve the highway congestion. In this paper, we propose a novel highway variable speed limit control system base on the Winternet Architecture. We use the STeC language to describe the system's formal model. Finally, we give control algorithm of the highway variable speed limit control system, which based on the formal model. The simulation results show the control algorithm is effective.

KEYWORDS

Intelligent Transportation System, Internet of things, Cyber-Physical systems, Winternet Architecture, spatio-temporal consistent, STeC language

1. INTRODUCTION

An efficient Intelligent Transportation System (ITS) is the most important method of reducing congestion and solving the traffic problems. The ITS infrastructures has already been used in highway to control the traffic flow and ease the traffic congestion. The research of the Internet of Things (IoT)[1] and the Cyber Physical Systems (CPS)[2] has been developed a lot of achievements in recent years, many novel methods and viewpoints can be introduced in the design and analysis of the Intelligent Transportation System.

With the highway's traffic flow growing, there is much more congestion in the highway. Contending with congestion in highway has long been recognized as one of the major priorities of most highway agencies. When there has been congested in the highway, we can groom the vehicles in the congested zone or restrict the vehicles move into the congested zone. Nowadays the main method of controlling the traffic flow moving into the congested zone is limiting the vehicles' speed before the congestion zone. This limiting the vehicles' speed system on the highway named Variable Speed Limit Controls System. It always recommends or enforces a reduced speed limit along the highway using variable speed signs.

Several researchers have studied the Variable Speed Limit Controls System. Coleman have made an automated speed management in Australia, which is a fog warning and speed advisory system installed south of Sydney[3]. In the same study, the also introduced a control system in Germany, which used a variable speed limit sign to display the current speed limit under the following types of scenarios: construction, fog, crash ahead, ice, and high winds. Pili-Sihvola introduced a variable speed limit control to warn drivers of black ice and other hazards in Finland[4]. A system in the United Kingdom described by Wilkie was designed to minimize the stop and go conditions during heavy traffic[5]. Likewise, Sumner has also reported a variable speed limit system in the

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state of New Mexico, which was intended to be flexible in responding to various environmental conditions[6]. Peiwei Lin has presented two online algorithms for variable speed limit controls at highway work zones that can take full advantage of all dynamic functions and concurrently achieve the objectives of queue reduction or throughput maximization[7].

Firstly, the above variable speed limit control systems always have been built based on the traditional sensors networks and their architectures are tightly coupled and closed. It is hard to upgrade and expand these. Nowadays, it is possible to build a distributed, opened, intelligent and scalable variable speed limit control system using the IoT or CPS viewpoints and methods. Cui Li divide the recently proposed architectures of IoT into two categories from the function perspective, namely back-end centralized and front distributed architectures, and comparatively analyze the in terms of horizontality, scalability, context-awareness, interactivity, adaptability and others[8]. Wei Zhao propose a novel IoT architecture, named Winternet and discuss its design principals, network topology, connection scheme and protocol stack[9].

Secondly, the above variable speed limit control systems always directly propose the system's control algorithm without the system's strictly formal description. Because it is very important to the design of the ITS based on the IoT, the temporality, the spatiality and the spatio-temporal consistency of the variable speed limit control systems should be seriously considered. The correct formal model is benefit to system design and can prevent to emerge design errors. The classical formal description language: Communication Sequential Process[10] and Calculus of Communicating Systems[11], can effectively describe the concurrent systems and communication systems. By introduced the time factor in the CSP and CCS, Timed CSP [12]and Timed CCS [13]can effectively describe the real-time systems. STeC language can not only describe the real-time systems, but also effectively describe the IoT systems which have the temporality, the spatiality and the spatio-temporal consistency[14].

Response to these two questions, we propose a variable speed limit control system using the Winternet Architecture on the Highway Congestion Zone in Section 2. In Section 3, we used the STeC language describe the system's formal model. And in Section 4, we give control algorithm of the variable speed limit control system, which based on the formal model. The simulation results show the control algorithm of the variable speed limit control system is effective.

2. THE ARCHITECTURE OF THE VARIABLE SPEED LIMIT CONTROLS WITH WINTERNET ARCHITECTURE ON HIGHWAY

The architecture of the traditional variable speed limit controls on highway like Fig. 1. The system always consists of a set of sensors which distributed along the highway, many variable speed limit signages on the highway and a central processing unit or controller. The control algorithms of the system have been implemented by the central controller. In these systems, the sensors along the road have sensed the data of the cars or the highway's environment, and then these data were transported to the central processor behind. The central processor has processed the data according to the control algorithm, and calculated the limit speed value. Finally, the limit speed data will be send to the speed limit signage on the highway and the signage will show the limit speed. Because the architectures of these traditional variable speed limit controls are always tightly coupled, this kind of system is difficult to communicate, exchange information or share data with the other systems.

The Winternet Architecture of the IoT has solved the above problems. The Winternet system used the Pipe protocol and it is built on the Internet protocols. So the Winternet systems can connect to other systems freely, and it is high real-time, privacy and proximity calculation.

Based on the Winternet architecture, we have built the variable speed limit controls on highway and its architecture like Fig. 2. In the system, all kinds of sensors along the highway and the variable speed limit signage are the Winternet Device Node components. These sensors can sense the vehicle's speed on the local highway and the signage can show the limit speed. There is a Winternet Backbone Node connect a Winternet Device Node. The Winternet computing component named Netlet were stored in the Winternet Backbone Node and it can process the raw data sent from the Winternet Device Node. The Winternet Access Node communicated with the WInternet Backbone Node by the Winternet pipe protocol, so they can exchange the information in time. However, a Winternet Access Node is not binding with another WInternet Backbone Node, they communicated by publishing /subscribe model.

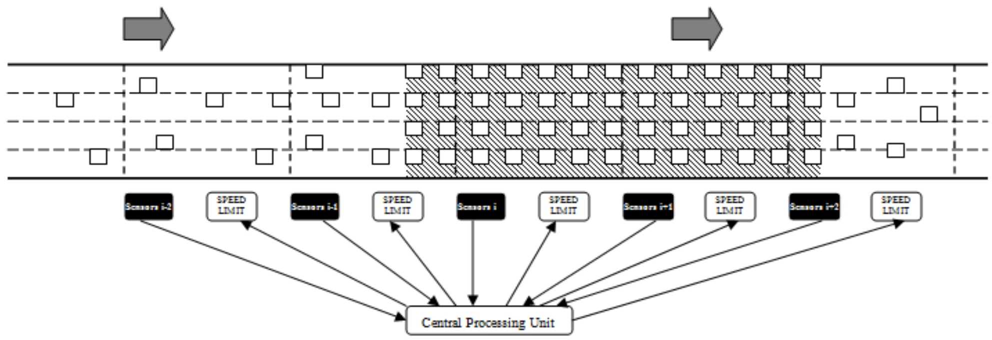

Figure 1. The variable speed limit controls with central processing unit

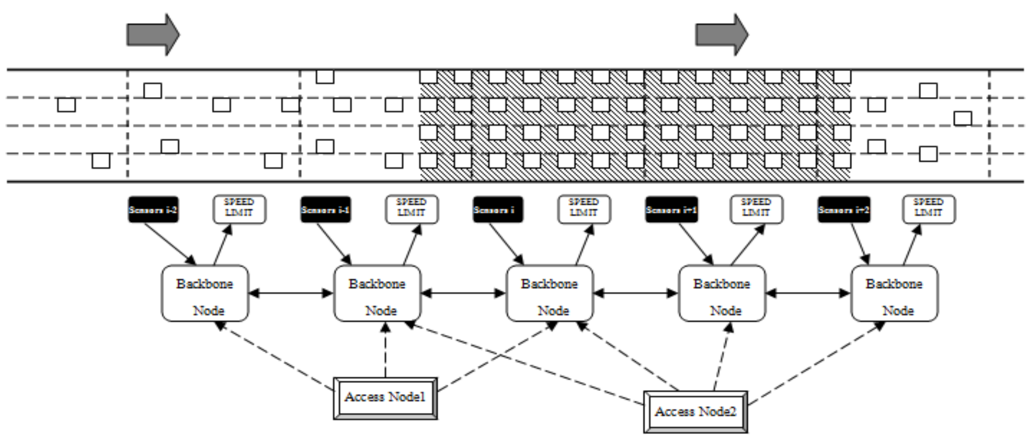

Figure 2. The architecture of the variable speed limit controls with Winternet architecture

The variable speed limit controls with Winternet on highway has four advantages: 1. The Winternet Backbone Node can process the raw data sent from the Winternet Device Node, and then it only send the processing results to the Winternet Access Node. So the transmission data between the Winternet Backbone Node and the Winternet Access Node are greatly reduced and the speed of data transmission between them is greatly increased. This is the foundation of the real-time controlling system. 2. In the system, the relationship between the Winternet Backbone Node and the Winternet Access Node is loosely coupled relationship. This relationship is benefit to upgrade and maintain the system. 3. The Winternet Backbone Node and the Winternet Access Node shared the system's data by the publishing \ subscribe model. This communication style is benefit to reuse and share the data. 4. Because the Winterent pipe protocol is based on Internet, it supports the different structure networks or systems to connect together. Therefore, the variable speed limit controls with Winternet on highway can connect either to the other Intelligent Transportation System or to the other kinds of variable speed limit controls.

After building the architecture of the variable speed limit controls with Winternet architecture, we should formal describe the system model and design the control algorithm. Next we will use the STeC language to describe the system model.

3. THE FORMAL MODEL OF THE VARIABLE SPEED LIMIT CONTROLS USING THE STEC LANGUAGE

The variable speed limit controls on the highway is the classical Internet of things or Cyber-Physical systems. Its formal model includes not only physical system such as the vehicle speed on the highway, the space between the vehicles and etc. but also information system such as the raw data were sensed by the sensors along the highway, the data from Winternet Backbone Node to Winternet Access Node. When modeled the formal model of the variable speed limit controls on the highway, we should select a specification language which can describe the temporality, the spatiality and the spatio-temporal consistency of the system. So we use the STeC language to model the system.

3.1. The Syntax of the STeC Language

The STeC language extends the formal language CSP and CCS. It can effectively describe the temporality and the spatiality of the agent's actions or status and the spatio-temporal consistency of the intelligent system. The language consists of the action keyword α, the status keyword β and the communication mechanism of the system. The STeC language syntax as below:

$$A ::= Send_{(l,t)}^{G\to G'}(m,\delta) \mid Get_{(l,t)}^{G\leftarrow G'}(m,\delta)$$

$$B ::= \alpha_{(l,t)}^{G}(l',\delta) \mid \beta_{(l,t)}^{G}(\delta)$$

$$P ::= Stop_{(l,t)} \mid Skip_{(l,t)} \mid A \mid B \mid P;P \mid$$

$$\square_{(i\in I)}(B_i \to P_i) \mid P \rhd_{\delta} P \mid$$

$$P \unrhd (Get_{(l,t)}^{G\leftarrow G'}(m) \to Q) \mid P \parallel P$$

The communications among the agents were express by two atom communication process: Send and Get. The atom communication process Send has defined the agent G send the message m to another agent G' at location l and time t. It take δunit time to implement the communication action. Like the action Send, the atom communication process Get has defined the agent G get the message m from another agent G' at location l and time t. It takeδunit time to implement the communication action. In STeC language, we have defined the action αand the status β for each agent. The action α means the agent implemented the task. $\alpha^{G}_{(l,t)}(l',\delta)$ means that the agent G has spent δ unit time to implement a task α at location l and time t and the agent G move to new location l'. So the agent will change their temporality and spatiality after their actions have been done. $\beta^{G}_{(l,t)}(\delta)$ means that the agent G has been in theβstatus during δ unit time at location l and time t. In the select process $\square_{(i\in I)}(B_i \rightarrow P_i)$, Bi is the condition. In STeC language, there is only a condition is true and the select process should select the condition and implement its Pi. The process $P \triangleright_{\delta} Q$ means that the process P has spent δ unit time then implement the process Q. The process $P \trianglerighteq (Get^{G\leftarrow G'}_{(l,t)}(m) \rightarrow Q)$ means that the agent implements the P process at first. When $Get^{G\leftarrow G'}_{(l,t)}(m)$ is true, the process P is halt and the process Q will be implement. However, the process P||Q means that the process P and the process Q have independently run at the same time.

3.2. The Formal Model of the Variable Speed Limit Controls Using the STeC Languag

In the variable speed limit controls, all kinds of agents' behavior can describe by STeC language. So we can model the system include of the physical components and the cyber components.

First of all, we model the evolution of congestion zone on the highway, which is part of physical components of the variable speed limit controls. The correct formal model will support the design of the control algorithm of the system. As figure 3 shows, the shaded part of the picture is the congestion zone (assume that there is a congestion when the vehicles average speed is below 20 km/hour), which named Zone 0. The area before the Zone 0 named Zone 1, where there is not jamming. And the area after Zone 0 named Zone 2, where the traffic flow has relieved congestion.

Assume that the sensors can sense the speed of the vehicles on highway per five seconds. So we can calculate the average speed in local area and conclude the length of the Zone 0 and the Zone 1. Assume that the length of the Zone 0 is L0, the changing process of the Zone 0 can be described by STeC language as below:

$$
\begin{aligned}
&LengthChanging_{(L_0,t)}(L_0-\Delta L_{0t}+\Delta L_{1t},5s);\\
&LengthChanging_{(L_0',t+5)}(L_0'-\Delta L_{0t}'+\Delta L_{1t}',5s);\\
&LengthChanging_{(L_0'',t+10)}(L_0''-\Delta L_{0t}''+\Delta L_{1t}'',5s);\\
&\ldots\\
&LengthChanging_{(L_0^{T-1},t+5(n-1))}(L_0^{T-1}-\Delta L_{0t}^{T-1}+\Delta L_{1t}^{T-1},5s);
\end{aligned}
$$

The above model describe that the length of the Zone 0 changes from L0 to L0 reduce the length of relieved congestion at that time ΔL0t then add the length of added congestion at that time ΔL1t . Because the aim of the variable speed limit controls is to limit the vehicle speed of Zone 1 and relieve the congestion of Zone 0, the length of the Zone 0 will change to zero at the end. Assume that it will take T0 unit time to relieve the congestion of Zone 0. This process model can be described as below:

$$LengthChanging_{(L_0,t)}(0,T_0);$$

The length of the Zone 0 and Zone 1 can be calculated by the formulas as below:

Assume that Ht is the distance between the vehicles at moment t and Vt is the vehicle speed at moment t. Their relationship as below:

$$H_t=f(V_t) \quad . \tag{1}$$

Assume that Constant C is the average of the vehicles and Mt is the maximum vehicles' quantity per km at moment t. Their relationship as below:

$$M_t=l/(C+H_t) \tag{2}$$

Assume that Nt is the real vehicles' quantity per km at moment t and Rt is the traffic density at moment t. Their relationship as below:

$$R_t=N_t/M_t \tag{3}$$

Assume that the original length of the Zone 0 is L0 and the reduced length of the congestion area is ΔL0t . So there will be:

$$\Delta L_{0t} = V_{0t} \times R_{0t} \tag{4}$$

Assume that the original length of the Zone 1 is L1 and the added length of the congestion area is ΔL1t . So there will be:

$$\Delta L_{1t} = V_{1t} \times R_{1t} \tag{5}$$

Assume that the congestion will be relieved after T unit time and the variation value of the length of the congestion is ΔL1t -ΔL0t at moment t. So we can conclude that:

$$\int_0^{\mathrm{T}} (\Delta \mathrm{L}_{1t} \text{-} \Delta \mathrm{L}_{0t} \ )\mathrm{dt} = \text{-}\mathrm{L}_0 \tag{6}$$

In the above formulas, the V1t in the formula (5) is the limit speed that should be show in the variable speed limit controls' signage at Zone 1. And the other variable in these formulas can be sensed by the sensors or calculated by the Winternet Backbone Node.

Following that, assume that the roadside sensors is Si,the Winternet Backbone Node is BNi,the Winternet Access Node is ANi and the Speedlimit Node is SNi, we should model the cyber components of the variable speed limit controls by STeC language:

First, the roadside sensors Si sensed the raw data （mcars）and transmit these data to its neighboring Winternet Backbone Node BNi. Since the BNi close the Si, the communication between them should use wireless or special-purpose phone line. Assume that it will take 0.02 seconds to transmit the data, the process of transmitting data will be described as below:

$$Send_{(L_i,t)}^{S_i \to BN_i}(m_{cars}, 0.01s); Get_{(Li,t)}^{BN_i \leftarrow S_i}(m_{cars}, 0.01s);$$

Second, after the Winternet Backbone Node get the data, it can calculate the local traffic density and the local average vehicles' speed according to the formula (1), formula (2) and formula (3). Assume that the calculating process will spend 1 second, it can be modeled as below:

$$Computing^{BN_i}_{(L'_i,t_1)}(L_i',1s);$$

Third, the Winternet Backbone Node sent the Vt and Rt (denoted as mcars') to the Winternet Access Node, which have already subscribed these data. Since their distance is always very long, they communicate each other by Internet. Assume that the data transmission will take 0.2 seconds, this process can be describe as below:

$$Send^{BN_i \to AN_i}_{(L_i',t_2)}(m_{cars}',0.1s); Get^{AN_i \leftarrow BN_i}_{(Li',t_2)}(m_{cars}',0.1s);$$

Fourth, the Winternet Access Node judge if there is Congestion at the area according to the received data. If there is congestion, it will compute the distance of the congestion zone. According to the formulas (6), we can calculate the limit speed. Then the Winternet Access Node will send the limit speed to the limit speed area's signage SNi (Speedlimit Node). These process can describe as below:

$$Judging^{AN_i}_{(L''_i,t_3)}(L_i'',1s);$$
$$Send^{AN_i \to BN_i'}_{(L_i'',t_4)}(m_{limit},0.1s); Get^{BN_i' \leftarrow AN_i}_{(Li',t_4)}(m_{\lim it},0.1s);$$
$$Send^{BN_i' \to SN_i}_{(L_i',t_5)}(m_{limit},0.01s); Get^{SN_i \leftarrow BN_i'}_{(Li',t_5)}(m_{\lim it},0.01s);$$

Finally, According to the formulas (6), the congestion will dismiss after T unit time. And then the Winternet Access Node will send the cancel the limit speed instruction to the limit speed area's Speedlimit Node SNi. These process can describe as below:

$$Send^{AN_i \to BN_i'}_{(L_i'',t_6)}(m_{cancel},0.1s); Get^{BN_i' \leftarrow AN_i}_{(Li',t_6)}(m_{cancel},0.1s);$$
$$Send^{BN_i' \to SN_i}_{(L_i',t_7)}(m_{cancel},0.01s); Get^{SN_i \leftarrow BN_i'}_{(Li',t_7)}(m_{cancel},0.01s);$$

The above formal model gave the clearly and Unambiguous foundation for designing the control algorithm of the variable speed limit controls.

4. THE CONTROL ALGORITHM AND THE SIMULATION OF THE VARIABLE SPEED LIMIT CONTROLS

4.1. The Control Algorithm of the Variable Speed Limit Controls

Based on the formal model of the variable speed limit controls, we designed the control algorithm of the system as below:

STEP1 : The roadside sensors send the raw data to the Winternet Backbone Node in time. These data include the vehicles speed and the distance between the vehicles etc.

STEP2 : The Winternet Backbone Node calculate the average speed and traffic density, then it transmit these data to the Winternet Access Node what have subscribed the data.

STEP3 : The Winternet Access Node judge if there is Congestion at the area according to the received data. If there is congestion, it will calculate the distance of the congestion zone and the limit speed. Then the Winternet Access Node send the limit speed to the limit speed area's signage SNi (Speedlimit Node).

STEP4 : The congestion will dismiss after T unit time. And then the Winternet Access Node send the cancel the limit speed instruction to the limit speed area's Speedlimit Node SNi.

4.2. The Simulation of the Variable Speed Limit Control

According to the above control algorithm of the variable speed limit controls, we have built the simulation by the Matlab/Simulink tools.

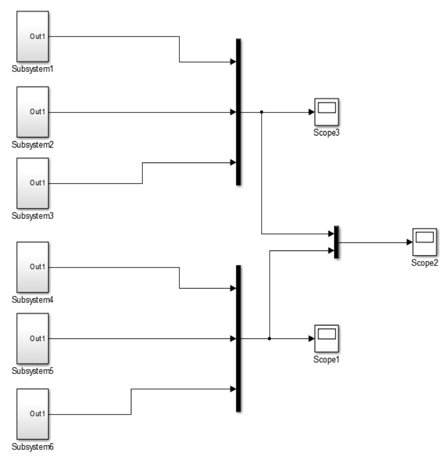

Figure 3. The Simulink simulation of the variable speed limit control

In the simulink simulation, we assume that the time unit is second, the distance unit is meter and the speed unit is kilometers per hour.

1)Using this simulation, we can find out the relationship between the length of the congested area (L0) and the locations about the limit speed signage (L1) as **Fig. 4**:

The simulation results show that, the location of limit speed signage gradually become longer with the growth of the distance of the congested area (L0) and the congested time. In the simulation, we assume the average vehicle speed in the congested area is 30 kilometers per hour.

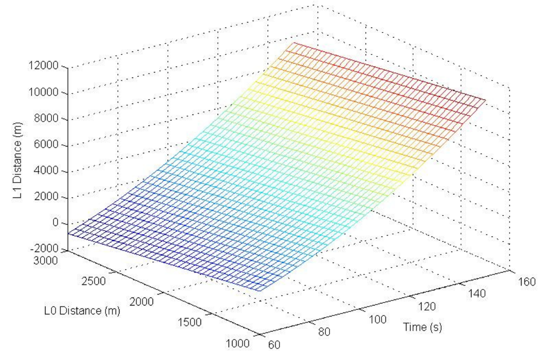

Figure 4. The relationship between L0 and L1

2) Using the simulation, we also can find out the relationship between the initial congestion distance and the relieve congestion time with the different congestion density. The simulation results as **Fig. 5**:

We set the simulation parameter as: the congestion distances are 3000m and 1000m, the limit speed is 30km/h, the vehicles flow density are 1.0, 0.6 and 0.3. The simulation results show that: according the different vehicles flow density, the relieve congestion time are 106s, 90s ,79s when the initial congestion distance is 3000m and the relieve congestion time are 76s,58s, 46s when the initial congestion distance is 1000m.

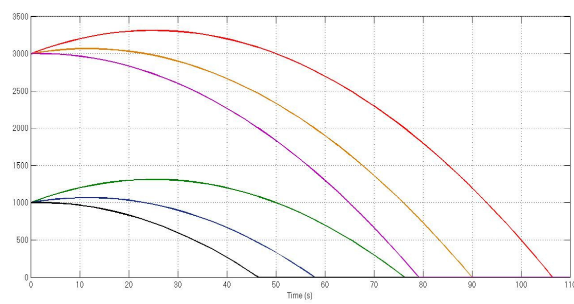

Figure 5. The relationship between the congestion distance and the relieve congestion time

3) Using the simulation, we can also find out the relationship between the initial average vehicles speed in the congestion area and the relieve congestion time. The results as **Fig. 6**:

We set the simulation parameter as: the initial distance of the congestion distance is 1000m, the initial average vehicles speed are 10km/h and 30km/h, the vehicles flow density are 0.3, 0.6 and 1.0. According to the different vehicles flow density, the relieve congestion time are 76s, 58s, 46s when the initial average vehicles speed is 30km/h in the congestion area and the relieve congestion time are 85s, 65s, 53s when the initial average vehicles speed is 30km/h in the congestion area. As the above picture shows: with the traffic flow density increasing, the relieve time is gradually increased.

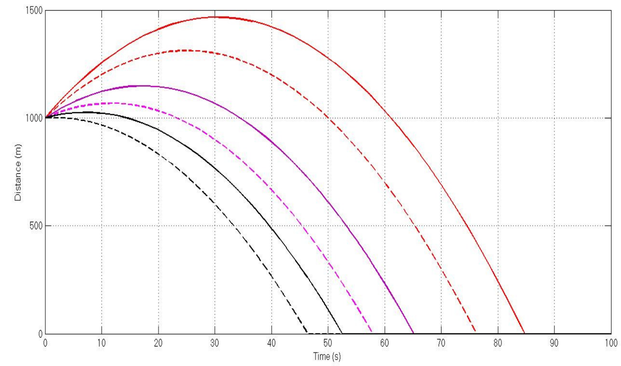

Figure 6. The relationship between the relieve congestion time and the initial vehicles

4) Using the simulation, we can find out the relationship between the initial congestion distance and the relieve congestion time. Their relationship as **Fig. 7**:

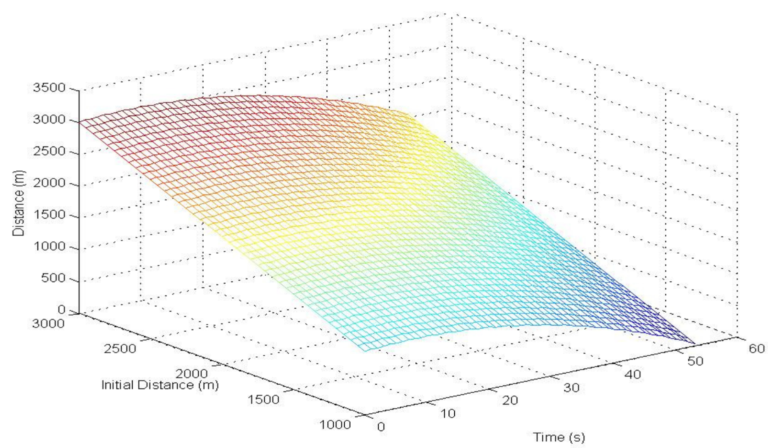

Figure 7. The relationship between the initial congestion distance and the relieve time

As the picture show: with the time increasing, the congestion distance gradually increasing at first, then it reach the highest point and gradually decline. And we also can see, the relationship between the initial congestion distance and the relieve time is a positive proportional relationship.

5. CONCLUSION

In brief, the architecture of the novel variable speed limit control system is distributed and loosely coupled. The STeC language formal model can effectively describe the system's spatio-temporal consistency. Finally, The simulation results show the control algorithm based on the formal model can effectively solve the highway congestion problem.

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REFERENCES

[1] L. Atzori & A. Iera, (2010) "The internet of things: A survey", Computer Networks, Vol.54, No.15, pp2787-2805.

[2] E. A & Lee, (2008)"Cyber physical systems: Design challenges", Object Oriented Real-Time Distributed Computing (ISORC), 11th IEEE International Symposium on. IEEE, pp363-369.

[3] J. A. Coleman & J. F. Paniati, (1996)"FHWA study tour for speed management and enforcement technology", US Department of Transportation, Washington, DC.

[4] Y. Pili-Sihvola & K. Taskula, (1996)"Mustaa Jaata and Finland's Weather-Controlled Road", Traffic Technology International, Vol.96, pp204-206.

[5] J. K. Wilkie, (1997)"Using variable speed limit signs to mitigate speed differentials upstream of reduced flow locations".

[6] R. L. Sumner & C. M. Andrew, (1990)"Variable speed limit system," US Department of Transportation, Federal Highway Administration.

[7] P. W. Lin & K. P. Kang,(2004)"Exploring the effectiveness of variable speed limit controls on highway work-zone operations," Intelligent transportation systems. Taylor & Francis Group, Vol.8, No.3, pp155-168.

[8] H. M & Chen, (2013)"A Comparative Study on Architectures and Implementation Methodologies of Internet of Things," Chinese Journal of Computers, Vol. 36, No.1, pp168-188.

[9] J. Wu & W.Zhao,(2013)"WInternet: From Net of Things to Internet of Things", Journal of Computer Research and Development, Vol.50, No.6, pp1127-1134.

[10] C. A. R. Hoare,(1978)"Communicating sequential processes", Communications of the ACM, Vol.21, No.8, pp666-677.

[11] R. Milner,(1982)" A calculus of communicating systems", Springer-Verlag New York, Inc.

[12] J. Davies & S. Schneider,(1995)"A brief history of Timed CSP", Theoretical Computer Science, Vol.138,No.2,pp243-271.

[13] W. Yi,(1991)"CCS+ time= an interleaving model for real time systems", Automata, Languages and Programming, Springer Berlin Heidelberg, pp217-228, 1991.

[14] Y. Chen,(2012)"Stec: A location-triggered specification language for real-time systems", Object/Component/Service-Oriented Real-Time Distributed Computing Workshops (ISORCW), 15th IEEE International Symposium on. IEEE, pp1-6.