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GPU Based Genetic Algorithms for the Dynamic Sub-area Division Problem of the Transportation System

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Abstract: At the early stage, the transportation system was controlled in a centralized way. As it grows larger, the system becomes decentralized. Nowadays, most of the commercial transportation systems work in a distributed way. The whole city or town is divided into static or dynamic sub-areas by some rules or heuristics. In every sub-area, the strategy is determined independently. As the cloud computing becomes popular, we propose the idea to control and management the transportation in a new centralized way, that is, all the information is collected together at the cloud side. The effect of the centralized control can be no worse than the decentralized one, as the decentralized control strategy is also one strategy of the centralized control. The division of the sub-areas is determined by computational experiments for different scenarios. We adopt the Multi-Agent System (MAS) model for the traffic flow simulation. And we use the Genetic Algorithms (GA) as the method for the computation to obtain good divisions. To overcome the difficult of the heavy computational burdens, we employ the Graphics Processing Unit (GPU) to accelerate the GA. We test the method on a 5×5 lattice road network and the 18 intersection Zhongguancun road network of Beijing. A speedup factor of around 110 is achieved.

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1. INTRODUCTION

Traffic jam is a serious problem for almost all big cities. There had been 451 million vehicles in Beijing until Sept. 2012. An average single commute takes more than 52 min (Niu, 2010). The first generation transportation system is controlled by the computer. The second generation is a centralized controlled system. It only applies to small systems with only a few intersections. The third generation transportation system, which is the most popular nowadays, takes use of distributed control of the whole network (Bazzan, 2005). We believe that, as the information and communication technologies (ICT) develop, especially the popularity of the cloud computing, the next generation will take the centralized control again. In principle, the strategy used at the distributed system can be applied at the centralized system as well, and the performance of the centralized system should be no worse than the distributed one. Moreover, if all the information is collected together, any division of the road network can be considered. It is quite possible that we do better than the distributed situation. This is alike to the development of the computers. At the old days, mainframes were popular. Later, people began to use the personal computers, which is a distributed way. And then, people find that the new centralized way of cloud computing has the advantage of shared resources and location-free services.

In this paper, we assume that all the information is collected as a whole. Following the research of (Mo et al., 2002 and Lu, et al. 2012), we use the Genetic Algorithms (GA) to optimize the sub-areas division. For a big city like Beijing, there are thousands of intersections. The computation burden can be heavy. We employ Graphics Processing Units (GPUs) to accelerate the GA. At the current stage, it is still difficult to solve the problem as large as Beijing. We test our method on small and medium large networks first. However, if limited to the two dimensions on the earth, a city cannot be much larger than cities such as Beijing, Tokyo and London. Currently, one GPU can run the simulation for millions of cars at the same time. We believe that, as the ICT develops, not far in the future we will be able to optimize the whole city as large as Beijing.

It is not easy to get a quantitative evaluation of the sub-area division strategy. We take use of the Multi-Agent System (MAS) in this paper (Wang, 2010, Wang and Tang, 2004). We employ GPUs to run the parallel simulations for the MAS (Shen et al., 2011, Wang and Shen, 2011, 2012a, 2012b).

Nevertheless, as the sub-areas far away from each other hardly interact with each other, we only need to consider sub-areas that are near to each other. How to determine the size of each sub-area? How to define "near"? We may need the gradient information regarding to the size and/or distance. The gradient may be estimated by computations. These are left for further research.

The contribution of this paper is to show the effects of using computational experiments (Wang, 2010) method to solve the problems in complex systems. The idea is to trade computation for intelligence. The remaining parts of the paper are organized as follow. In Section 2, we give the literature review on the sub-area division problem, on the GA, and on the GPU. In Section 3, we describe the problem. In Section 4, we show how the method is applied. In Section 5, we show experiments. In Section 6 we give conclusions and discussions.

2. LITERETURE REVIEW

2.1 Transportation Region Division Problem

The literature (Robertson and Bretherton, 1991) points out that the implementation of the regional multi-intersection coordination control can reduce the delay time and the average stop times by 10% to 40%. However, if the coordination region is the entire city, the computation burden will be so huge that the calculation speed is difficult to meet the needs. To solve this problem, R. J. Walinchus proposes to divide the urban road network into multiple independent sub-areas. The optimization and implementation of coordination control strategies are all carried out in the sub-areas (Walinchus, 1971).

The correlation degree is a quantitative description of relevance between two adjacent intersections. The correlation degree is affected by the distance, traffic flow, and the signal timing parameters between two adjacent intersections. In the 1960s, the traffic coordination control systems like TRANSYT, SCOOT and SCATS were integrated with sub-area division methods.

The concept of adjacent intersection correlation was proposed by H. Yagoda in 1973. He points out that two adjacent intersections should be included in the same sub-area when the correlation degree is more than 0.5. The correlation degree between two adjacent intersections is defined as follows,

$$I_{ij} = Vol/L, \tag{1}$$

where I_{ij} is the correlation degree between intersection i and intersection j, Vol is the traffic flow of the link between this two intersections, and L is the length of the link.

Various factors that affect correlation degree should be taken into consideration, such as the length of the link, characteristics of traffic flow, the phase sequence of signal and volatility of traffic flow over time. It is suggested that two intersections should be included in the same sub-area when the length of link between them is less than 610m. The U.S. Federal Highway Administration suggested two intersections could be included in the same sub-area when the length is less than 800m.

Based on the Whitson model, E. C. P. Chang (Chang, 1986) proposed a model as follows,

$$I_{ij}=\left(1/(1+t)\right)\cdot\left(x\cdot q_{\max}\Big/\sum_{k=1}^{x} q_k\right)-(N-2) \tag{2}$$

where t is the time with the unit minute, x is the number of traffic flow that flow into the same upstream intersection, q_1, q_2, …, q_x are the flows going into the upstream intersection, $q_{\max}$ is the maximum flow of all traffic flows, N is the number of lanes in the downstream intersection. There is no need for the coordination control when $I_{ij} < 0.25$. When $I_{ij} > 0.5$, the two adjacent intersections should be included in the same sub-area. In other cases, it depends on the actual conditions.

K. Lu (Lu et al., 2012) and his colleagues take the length of the links, traffic flow and signal control parameters into consideration, and give the definition of correlation degree as follows,

$$\begin{aligned} I_{ij}={}&D_{\mathrm{S}(I_x,I_y)}+D_{\mathrm{C}(I_x,I_y)}=\left((N_E+N_A)\cdot L_V/(N_L\cdot L_L)\right)\cdot K_{L_L}\cdot K_N \\ &-\min\{(C_{\max}/C_{\min})/\lfloor C_{\max}/C_{\min}\rfloor-1, \\ &\qquad\lfloor C_{\max}/C_{\min}+1\rfloor/(C_{\max}/C_{\min})\}\cdot K_C, \end{aligned} \tag{3}$$

where $D_{\mathrm{S}(I_x,I_y)}$ stands for the correlation degree with respect to the traffic flow, $D_{\mathrm{C}(I_x,I_y)}$ stands for the correlation degree with respect the cycle, N_E is the number of vehicles in the link (road), N_A is the maximum of the possible increment of vehicles in next cycle, N_L is the number of lanes that vehicles occupy, L_V is the average length of vehicles, L_L is the length of the link (road), K_{L_L} is the compensation factor of the traffic flow, K_N is the scaling factor (empirical value 2), K_C is the weighting factor for relevance of the cycle (empirical value 0.5), and $C_{\min}, C_{\max}$ are the minimum and maximum values of the cycle. It is suggested that there should be no need for coordination control when $I_{ij} < 0.2$, and, the two adjacent intersections should be included in the same sub-area when $I_{ij} > 0.8$.

In summary, most definitions of the correlation degree take the length of the links, traffic flow and signal timing parameters into consideration, and specify the judging thresholds. Although varying from one to another, the definitions are confined to two adjacent intersections. The case that the correlation between the intersections that are not adjacent to each other is not considered. The mutual influence may exist between non-adjacent intersections. The correlation of intersections should not be restricted to two adjacent intersections.

Most previous studies aim at the division of small scale road network. Usually macroscopic model traffic flow is used, which can provide relatively accurate performances. In recent years, with the increasing scale of urban road network, Intelligent Transportation Systems (Chen and Cheng, 2010, Wang, 2010, Li et al., 2012, Li et al., 2013, Shen et al., 2011, Strippgen and Nagel, 2009a, Strippgen and Nagel 2009b, Wang and Tang, 2004, Wang and Shen, 2011, 2012abc) have been widely used and become more and more popular. Because drivers' behaviours are affected by many factors, it is difficult to establish an accurate macroscopic model for transport system. A microscopic model such as the Multi-Agent System (MAS) model is desirable. Here in this paper we take the MAS model (Chen and Cheng, 2010, Shen et al., 2011, Wang and Shen, 2011, 2012) for the evaluation of the division of sub-areas.

2.2 Genetic Algorithms and GPU

The GA was proposed by Prof. J. Holland in 1975 (Goldberg and Holland, 1988). Now GA is a very popular technique for optimization of complex systems. In hardware, a GPU has many cores working together. The cores are called Streaming Processors (SP), and several cores (8 or 32 typically) are organized into a Streaming Multi-processor (SM). In software, a typical GPU program consists of two parts: one part is the CPU codes that control the process of the whole program and does the sequential work, and the other is the GPU part that does the parallel work. When applying GA with GPU, the parallel part works on GPU while the sequential part still works on the CPU. The method has been applied in solving the Quadratic Assignment Problem (QAP) (Tsutsui and Fujimoto, 2009) and traffic signal timing optimization problem (Shen et al., 2011).

3. PROBLEM DESCRIPTION

3.1 Problem Formulation

According to (Mo et al., 2002), the road network is divided depending on the different traffic characteristics of different areas. Every sub-area employs different control strategy that is suitable for itself. All the sub-areas are relatively independent from the others.

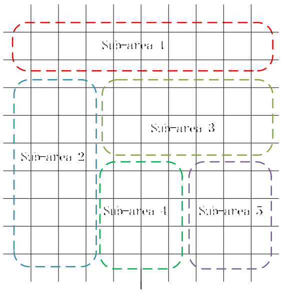

Fig. 1. The traffic sub-areas

As Fig. 1 shows, the traffic road network can be described by the graph model $G(V,E)$, and the traffic sub-area can be described as follows,

$$\begin{cases} G = G(V,E) \\ V = \{v_1, v_2, \cdots, v_n \,|\, n \geq 2\} \\ E = \{< v_i, v_j > \,|\, v_i, v_j \in V\} \\ I = \{I_{ij}(t) > I_{\min} \,|\, 0 \leq t \leq T\}, \end{cases} \tag{4}$$

where V is the set of nodes in the figure, E is the set of links (edges in a graph), $v_1, v_2, \cdots, v_n$ stand for the nodes in the figure, $< v_i, v_j >$ stands for the links, I is the set of the intersections that are included in the same sub-area. $I_{ij}(\bullet)$ is the variable that measures the correlation degree of traffic conditions between the adjacent nodes, t is the time variable, T is the time period that we concern, and $I_{\min}$ determines whether two adjacent nodes should be included in the same sub-area. When $I_{ij}(t) > I_{\min}$, the nodes v_i, v_j should be included in the same sub-area. When $I_{ij}(t) \leq I_{\min}$, they should not.

3.2 Influencing Factors

The key point of the sub-area division is to determine the specific expression of $I_{ij}(\bullet)$ and the value of $I_{\min}$. According to (Lu et al., 2012), the traffic correlation is related primarily to the following factors.

- Distance factor. When the distance between two intersections is long, it takes a long time for the vehicle to go from the upstream node to the downstream node. When the distance is short, we should implement the coordination control to consider the two nodes as a whole.
- Cycle factor. If the cycle periods are approximate the same between two intersections, the traffic conditions of two intersections should be similar, so that we put two intersections into the same sub-area.
- Flow factor. When the traffic flow between two intersections is large, the two intersections should be included in the same sub-area, so that the vehicles between two intersections could move fast.

The three major factors can be sorted into the two categories: static and dynamic. The distance is decided by the actual road network topology and is static, while the signal control cycle and traffic flow are changing over time. Nowadays, popular traffic control systems are TRANSYT, SCOOT and SCATS. The TRANSYT and SCOOT apply the static division strategy, while SCATS uses a semi-dynamic division strategy.

3.3 Modelling the Division

To guarantee the overall performance of regional coordination control, we follow the literature (Lu et al., 2012), who propose to combine correlations of multiple intersections. Similar to the two adjacent intersections case, the correlation of multiple intersections include two parts: degree of traffic flows and degree of the cycles,

$$\begin{aligned} & D_{(I_1,I_2,\ldots,I_n)} = D_{\mathrm{S}(I_1,I_2,\ldots,I_n)} + D_{\mathrm{C}(I_1,I_2,\ldots,I_n)} = \\ & \prod_{k=1}^{m} F(D_{S_k}) + \min\left\{ D_{\mathrm{C}(I_x,I_y)} \,\middle|\, I_x, I_y \in \{I_1, I_2, \ldots, I_n\} \right\}, \end{aligned} \tag{5}$$

where $D_{(I_1,I_2,\ldots,I_n)}$ is the correlation of intersections $I_1, I_2, \ldots, I_n$, $D_{\mathrm{S}(I_1,I_2,\ldots,I_n)}, D_{\mathrm{C}(I_1,I_2,\ldots,I_n)}$ are the correlations of the traffic flows and the cycle respectively, m is the number of correlated intersections, and D_{S_k} is the correlation degree of the k-th two adjacent intersections. $F(D_{S_k})$ is shown as follows,

$$F(D_{S_k}) = (\min\{D_{S_k}, \mathrm{sign}(D_{S_k})\})^{1/k}, \tag{6}$$

where $\mathrm{sign}\{\bullet\}$ is the sign function. We define D_{S_k} as follows,

$$\{D_{S_1},D_{S_2},\ldots,D_{S_m}\}=\text{sort}\{D_{S(I_1,I_2)},\ldots,D_{S(I_{n\text{-}1},I_n)}\}, \tag{7}$$

where $\text{sort}\{\bullet\}$ is the ascending sort function, and it means that all m pairs of adjacent intersections will be assigned to $D_{S_1},D_{S_1},\ldots,D_{S_m}$ in order, after the ascending sorting.

After obtaining the correlation of intersections, the sub-area division problem can be modelled as follows,

$$\max PI=-N_{TS}^{K_P}+D_{TA}$$
$$\text{s.}t.$$
$$\begin{cases} I_x,I_y\in\{I_1,I_2,\ldots,I_n\} \\ R_{(I_x,I_y)}\in\{R_1,R_2,\ldots,R_m\} \\ R_{(I_x,I_y)}=0\big|_{D(I_x,I_y)<D_{TNS}} \\ R_{(I_x,I_y)}=1\big|_{D(I_x,I_y)\geq D_{TNC}} \\ D_{A_i}>D_{TMS} \\ N_{TS}=F_{NS}(R_1R_2\ldots R_m) \\ D_{TA}=\sum_{i=1}^{N_{TS}}D_{A_i} \end{cases} \tag{8}$$

where $I_1, I_2,\ldots, I_n$ and $R_1, R_2,\ldots, R_m$ represent n intersections and m roads in the road network, $R_{(I_x,I_y)}=0$ indicates that two adjacent intersections I_x, I_y are not correlated closely, so that they should be divided into different sub-areas, while $R_{(I_x,I_y)}=1$ has a contrary meaning, $D_{(I_x,I_y)}$ is the correlation degree between two adjacent intersections I_x, I_y, D_{TNS} and D_{TNC} are the thresholds of separation and merging of two adjacent intersections, D_{A_i} is the correlation of the sub-area constituted by the intersection set A_i, D_{TMS} is the separation threshold of multiple intersections, N_{TS} is the total number of sub-areas after division, $F_{NS}(\bullet)$ is the function to obtain the number of sub-areas, D_{TA} is the sum of correlation degrees of sub-areas in the road network, PI is the evaluation function of division strategy, and K_P is the weighting coefficient of sub-area number.

The objective of sub-area division is to maximize the evaluation function PI, i.e. to maximize the sum of correlation degrees of all sub-areas and minimize the number of sub-areas.

4. APPLICATION OF GPU BASED GA

4.1 Solution Based on GA

The application of GA described as follows.

Step 1: Calculate the correlation degree $D_{(I_x,I_y)}$ of all adjacent intersections. When $D_{(I_x,I_y)}<D_{TNS}$ or $D_{(I_x,I_y)}\geq D_{TNC}$, there is no need for the encoding operation.

Step 2: If the correlation degree of adjacent intersections belongs to the interval $[D_{TNS},D_{TNC})$, encode the related roads, and obtain a sub-area division strategy. Generate the initial population with the same method.

Step 3: Take PI as the fitness function, and calculate the correlation degree of all strategies in current population.

Step 4: To get a new population by the crossover, mutation and selection operations to the initial population.

Step 5: Repeat step 3 and 4 until meeting the exit criteria, and take the individual with the highest correlation degree as the final strategy.

An example of the division is shown in Fig. 2.

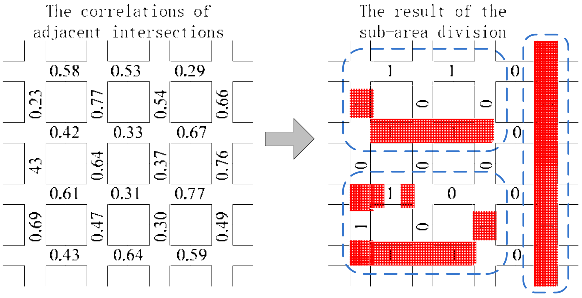

Fig. 2. An example for the sub-area division

4.2 Parallel Method

Microscopic simulation model and GA both can be parallelized as described below.

- Because of randomness in computing the correlation degree of adjacent intersections, we need multiple independent runs to obtain a traffic flow evolution. Multiple runs of the simulation model can be parallelized. In our simulation system, vehicles, lanes, intersections, and the road networks are "mapped" to threads, blocks, rows of blocks and grids for the GPU to compute.
- In the GA, the evaluations about different division strategies in the population are independent with each other. It can be parallelized.

Please refer to the papers of the same authors (Shen et al., 2011, Wang and Shen, 2011, 2012c) for details.

5. EXPERIMENTS

We test the sub-area division strategy on a 5×5 lattice road network and an 18 intersection Zhongguancun road network of Beijing. We take (1) instead of (3) for the correlation degree between two intersections, that is, we assume the cycle time is the same and do not consider the cycle factor. We follow (5)~(8) for the correlation of multiple intersections. We set $D_{TNS}=0.2$, $D_{TNC}=0.8$, $D_{TMS}=0.2$, $K_p=2$. We assume that the vehicles follow a Poisson process. We test three levels: 0.01 vehs/s, 0.1 vehs/s and 1 vehs/s. The simulation time is set as 10,800 s. The time step is set to be 1 s. The data about the correlation degree of adjacent intersections are based on 100 independent runs. The parameters of GA are set as follows. The number of generations is set to 1,000, and the size of population is 200. The crossover and mutation possibilities are 0.95 and 0.05

respectively. The workstation we use has two Intel SandyBridge six-core 2.0 GHz E5-2620 CPUs, and an NVIDIA Tesla C2075 GPU.

5.1 Dynamic Division of the Lattice Road Network

We consider the 5×5 lattice road network, and the vehicle generating position is at the centre. Please see Figs. 3~6.

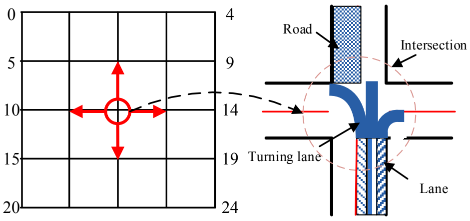

Fig. 3. The vehicle generating position is at in the centre

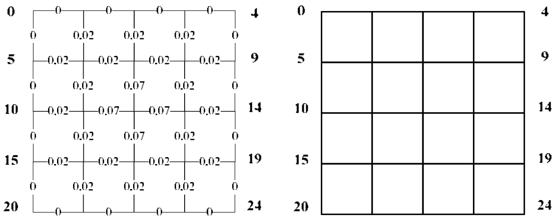

Fig. 4. The correlation degrees and the division ($\lambda = 0.01$)

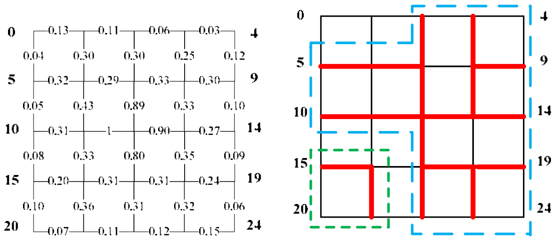

Fig. 5. The correlation degrees and the division ($\lambda = 0.1$)

From the experiment results, we can see that the values of all correlation degrees are less than 0.2 when $\lambda = 0.01$, so that there is no need for the coordination control. For the case $\lambda = 1$, there is almost no correlation degree less than 0.2. The entire area needs to be controlled as a whole.

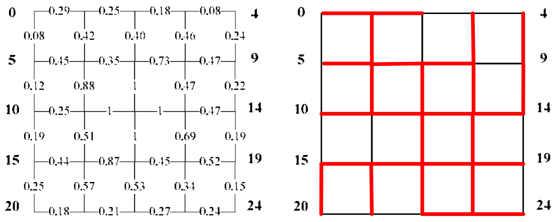

Fig. 6. The correlation degrees and division ($\lambda = 1$)

Furthermore, we compare the GPU based parallel method with the sequential method based on CPU only. Here we choose $\lambda = 1$ as the experiment case. Please see Table 1.

Table 1. The comparison between two methods

	CPU	CPU+GPU	Speedup
Average time /s	10075.77	89.25	**112.89**
Standard deviation	103.58	5.57	N/A

5.2 Dynamic Division of the Zhongguancun Area of Beijing

There are two positions for the vehicles to appear, marked in Fig. 9. The experiment results are shown in Figs. 7~12.

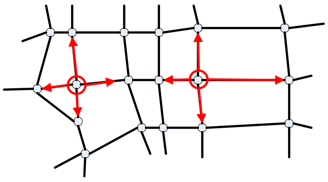

Fig. 7. Zhongguancun area road network

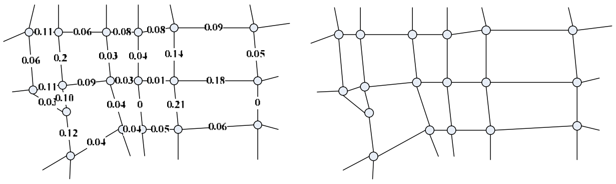

Fig. 8. The correlation degrees and the division ($\lambda = 0.01$)

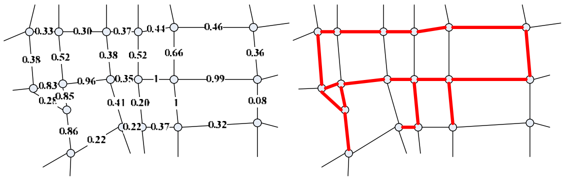

Fig. 9. The correlation degrees and the division ($\lambda = 0.1$)

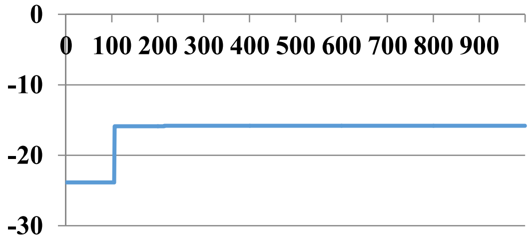

Fig. 10. The convergence ($\lambda = 0.1$)

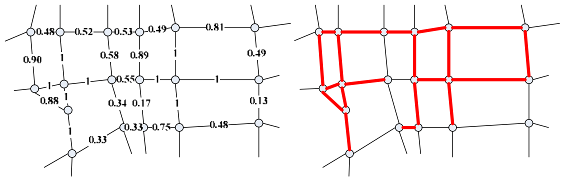

Fig. 11. The correlation degrees and the division ($\lambda = 1$)

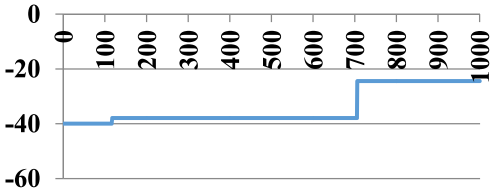

Fig. 12. The convergence ($\lambda = 1$)

In Table 2 we show the comparison between the CPU only implementation and the GPU, for the case $\lambda = 1$.

Table 2. The comparison between two methods

	CPU	CPU+GPU	Speedup
Average time /s	9361.47	85.38	**109.64**
Standard deviation	17.81	2.77	N/A

6. CONCLUSIONS AND DISCUSSIONS

In this paper, we show how to solve the dynamic sub-area division problem with the Genetic Algorithms (GA) based on the Graphics Processing Unit (GPU). The GPU plays an important role in accelerating the computation. A speedup factor of around 110 is achieved. As reported in (Wang and Shen, 2012c), for a lattice road network as small as 5×5, the speedup factor is 1.85. Only when the network is as large as 40×40, the speedup factor is 105.13. The speedup for traffic simulation mainly depends on the number of vehicles, as the vehicles are "moved" in sequential on CPU but in parallel on GPU. We have 100 independent runs of simulations here in this paper. The speedup comes mainly from the parallel evaluation of the runs of simulations and the individuals in a generation, not from a single run of the traffic simulation.

The computation cost makes the real time application of the method almost impossible. But we can perform many computational experiments to calculate the suitable dynamic strategies for all typical scenarios. When applying the method, we only need to identify which scenario it is and choose the suitable division method. Also, we should investigate the computational experiments further to solve large scale problems. These are left for further research.

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