

Methods for Division of Road Traffic Network for Distributed Simulation Performed on Heterogeneous Clusters

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Abstract. The computer simulation of road traffic is an important tool for control and analysis of road traffic networks. Due to their requirements for computation time (especially for large road traffic networks), many simulators of the road traffic has been adapted for distributed computing environment where combined power of multiple interconnected computers (nodes) is utilized. In this case, the road traffic network is divided into required number of sub-networks, whose simulation is then performed on particular nodes of the distributed computer. The distributed computer can be a homogenous (with nodes of the same computational power) or a heterogeneous cluster (with nodes of various powers). In this paper, we present two methods for road traffic network division for heterogeneous clusters. These methods consider the different computational powers of the particular nodes determined using a benchmark during the road traffic network division.

Keywords: road traffic simulation, network division, distributed simulation, heterogeneous clusters.

1. Introduction

The computer simulation of road traffic is an important tool for control and analysis of existing or designed road traffic networks. However, a run of a detailed simulation of a large road traffic network (e.g. entire cities or even states) can be very time-consuming. Moreover, very often, multiple simulation runs are required in order to ensure fidelity of the collected results. Hence, many simulators of the road traffic have been adapted for the distributed computing environment. There, the combined power of multiple interconnected computers (nodes) is utilized for speedup of the simulation.

The adaptation for the distributed computing environment usually means that the road traffic network is divided into required number of sub-networks. Simulations of these sub-networks are then performed as processes on particular nodes of the distributed computer. In order to fully exploit the power

of each node and therefore maximize the speed of the distributed simulation, the particular sub-networks should be load-balanced.

If the computer, on which the simulation is running, is a homogenous cluster (i.e. with nodes of the same computational power), the load of the particular sub-networks should be similar. Nevertheless, quite often, the nodes of the distributed computer can be of different computational power (e.g. various desktop computers interconnected by Ethernet in a university campus). For such a heterogeneous cluster, the load-balancing means that the load of each sub-network is adapted for the computational power of the node, on which the simulation of this sub-network will be performed.

In the remainder of this paper, two methods for road traffic network division for heterogeneous clusters are described. These methods consider the different computational powers of the particular nodes during the division. The information about the actual power of each node is determined using a set of tests (i.e. a benchmark) rather than using the information about the processor speed, memory size, and so on. The methods have been thoroughly tested and compared each other and with methods for homogenous clusters. The results of the testing are part of this paper as well.

2. Distributed Road Traffic Simulation

The methods for division of road traffic networks presented in this paper are designed for distributed discrete time-stepped microscopic simulation of road traffic. Moreover, the methods themselves utilize less-detailed road traffic simulations. Hence, the basic features and issues of the road traffic simulation and its distributed version are briefly described in following sections.

2.1. Time-Flow Mechanism of the Simulation

One of the most important features of a general simulation is the way the simulation time is advanced (i.e. a time-flow mechanism). There are two commonly used approaches – the *time-stepped* time flow mechanism and the *event-based* time-flow mechanism [1].

Using the time-stepped time-flow mechanism, the entire simulation time is subdivided into sequence of equally-sized time steps. The length of the time step is often set to one second. In each time step, the entire simulation state is recomputed [1].

Using the event-driven mechanism, the simulation time is subdivided into sequence of events. With each event, an action and a time stamp are associated. The action is an incremental change of the simulation state and the time stamp determines when this change shall happen [1].

2.2. Level of Detail of the Road Traffic Simulation

There are several types of road traffic simulation, which can be most commonly divided based on the level of detail into *macroscopic*, *mesoscopic*, and *microscopic* simulations.

In a macroscopic simulation, the traffic in particular traffic lanes is represented by traffic flows described by set of parameters (e.g. mean speed, vehicle density, etc.). These parameters are periodically recomputed. The macroscopic simulations are the oldest ones [2] and exists in many modifications. Both mentioned time-flow mechanisms (see Section 2.1) are commonly used. Since there are no vehicles considered in the simulation and the traffic flows are represented only by a limited number of parameters, the macroscopic simulation can be very fast. It is often possible to simulate a very large road traffic network faster than in a real time on a standard desktop computer [3].

The microscopic simulation represents the opposite side of the road traffic simulations field. In this simulation type, every single vehicle is considered with its own position, direction, speed, and acceleration. The positions of the vehicles are periodically recomputed based on their current speed and the utilized traffic model. Two basic models are commonly used – the *cellular automaton model* [4] and the *car-following model* [5]. Using the cellular automaton model, the traffic lanes are divided into equally-sized cells. The vehicles can be placed only into these cells and are moving from a cell to another based on their current speed. Using the car-following model, the vehicles can be placed anywhere in the traffic lane. The first vehicle in the lane can move freely, but the other vehicles must respect the speed of the vehicles in front of them. In both models, the vehicles tend to accelerate to a maximal speed, if there are no obstacles (e.g. a slower vehicle) in their way, and slow down or even stop otherwise [4], [5]. A random slowdown is often used as a component of the speed of the vehicles in order to model its natural fluctuations due to the traffic conditions [4]. Regardless the utilized traffic model, in the vast majority of the microscopic road traffic simulations, the time-stepped time-flow mechanism is used (for example, see [6] and [7]). Due to the high detail of the simulation, the collected results are more precise, but the simulation runs are very time-consuming, especially for large traffic networks. The majority of the computation time is usually consumed by the movement of the vehicles [8].

The mesoscopic simulation lies between the macroscopic and the microscopic simulations described in previous paragraphs. There are many various approaches, which are considered mesoscopic, such as queuing networks [9] or gas-kinetic models [10]. However, the common characteristic is that there is a representation of the vehicles, but their interactions are modeled at very low detail [11]. So, a mesoscopic simulation can be much faster than a microscopic simulation. Both time-flow mechanisms are commonly used.

2.3. Decomposition of the Road Traffic Simulation

When a road traffic simulation is prepared for the distributed computing environment, it must be decomposed in some way in order to be performed on more than one computer (or node). There are several general types of decomposition of a simulation. However, in the field of road traffic simulation, the *spatial decomposition* is most common. Using this approach, the road traffic network is divided into a required number of sub-networks (i.e. parts of the original road traffic network). Simulation of each sub-network is then performed as a process on a node of the distributed computer.

The number of sub-networks often corresponds to the number of nodes of the distributed computer (to maximize efficiency). Nevertheless, it is possible to perform more simulation processes on one node [7]. If the node has multiple processors or multiple processor cores, this can lead to further speedup of the simulation and better exploitation of the node's computational power [12]. In this paper, we will not consider this possibility further, unless otherwise stated.

There are other approaches to the simulation decomposition, such as *task parallelization* or *temporal decomposition*. Since their utilization in the field of road traffic simulation is very rare (some examples can be found in [13] and [14], respectively), we will not consider them further.

2.4. Inter-process Communication in Distributed Traffic Simulation

Using the spatial decomposition, the road traffic network is divided into required number of sub-networks, which are then simulated by simulation processes running on the particular nodes of the distributed computer. These sub-networks were originally interconnected by a set of traffic lanes, which are divided during the decomposition. However, the interconnection of the sub-networks must be maintained in the distributed simulation in order to enable passing of the vehicles in the divided lanes. For this purpose, communication links are established among the simulation processes. The vehicles passing from one sub-network to another are then transferred as messages between the corresponding simulation processes [3].

Besides the transfer of vehicles, it is also necessary to ensure the consistency of the entire distributed simulation. This means that all vehicles passing among the sub-networks must arrive to the target sub-network in correct simulation time. Otherwise, a causality error occurs [1]. Considering the time-stepped time-flow mechanism only (see Section 2.1), this means that a vehicle arrives in an incorrect time step (i.e. past or future). So, all simulation processes must perform the same time step at the same moment to maintain the consistency of the distributed simulation. This is ensured by a synchronization mechanism based on a synchronization barrier. This mechanism allows the simulation process to continue with next time step after all simulation processes finished the computation of the previous time

step. The barrier can be implemented in a separate process running on another node of the distributed computer or can be distributed [3].

Both the transfer of vehicles and the synchronization are maintained by a communication protocol of the distributed road traffic simulation. Because the inter-process communication is relatively slow in comparison to the remainder of the computations of the distributed simulation, it is convenient to reduce it. This can be achieved in several ways, for example by aggregation of more vehicles into one message spatially (vehicles from more traffic lanes) or temporally (vehicles from more time steps). A detailed discussion of the possibilities of the reduction of inter-process communication is outside the scope of this paper, but further information can be found in [3]. Nevertheless, the communication can be positively influenced even by a convenient division of the traffic network when the number of divided traffic lanes is minimized (see Section 3).

2.5. Distributed Road Traffic Simulator for Testing

The methods for division of road traffic networks described later in the text have been tested using the Distributed Urban Traffic Simulator (DUTS), which has been developed at Department of Computer Science and Engineering of University of West Bohemia (DSCE UWB). It is a distributed discrete time-stepped simulator of urban road traffic, but can be performed on a single-processor computer as well [15].

The simulator incorporates three traffic models inspired by three existing road traffic simulators – one car-following model (inspired by the AIMSUN [16] simulator) and two cellular automaton models (inspired by the JUTS [17] and TRANSIMS [6] simulators, respectively). Because the methods for the division of road traffic networks are independent on the traffic model utilized for the simulation, only the JUTS-based traffic model was used for testing. The reason is that this model has medium computational demands from all three models [3].

The DUTS simulator also incorporates several communication protocols of different efficiency. For the testing, a basic SC-LV (Semi-Centralized Lane Vehicles) rather than an advanced communication protocol was used. The SC-LV protocol transfers all vehicles from one traffic lane in one time step in one message. Usually, each message contains only one vehicle. However, if there are two or more vehicles traveling from a sub-network to a neighboring one in one traffic lane in one time step, they are transferred together in one message [3]. The synchronization is performed in every time step using a control process with a centralized barrier. Each working process simulating a traffic sub-network exchanges two messages with the control process per time step [3]. The SC-LV protocol was used because similar protocols are used in many existing distributed road traffic simulators. More importantly, it enables better testing of the quality of the methods for division of road traffic networks regarding the number of divided traffic lanes. A more advanced protocol could mitigate the influence of the number of divided traffic lanes [3].

3. Common Approaches to Road Traffic Network Division

Now, as we discussed the general features and issues of the distributed road traffic simulation, we can focus on the road traffic network division. There are two main issues, which should be considered during the road traffic network division – the load-balancing of the resulting sub-networks and the inter-process communication. Both issues are important for the resulting performance of the distributed road traffic simulation, for which the road traffic network is divided.

The load-balancing is important because of the synchronization. All simulation processes perform the same time step at the same moment (see Section 2.4). This means that the faster processes must wait until the slower processes finish the computation in each time step [3]. Hence, it is desirable for all simulation processes to consume similar amount of time for the computation of each time step [18]. If the distributed computer is a cluster of homogenous computers, the road traffic network should be divided into sub-networks with similar load (i.e. similar numbers of vehicles moving within the sub-networks).

The inter-process communication is important, because it is very slow in comparison to the remainder of the computations of the distributed simulation. Hence, it is desirable to reduce the inter-process communication to the necessary minimum. Because the communication is necessary primarily for the transfer of vehicles among the sub-networks, its intensity depends on the number of traffic lanes divided during the road traffic network division and also on the vehicle densities in these lanes [3].

There are several existing approaches to the road traffic network division, which can but do not have to consider the mentioned issues. Some of them are described in following sections.

3.1. Division without Any Optimization

The easiest approach is to divide the road traffic network into equally-sized rectangular pieces (sub-networks). Using this division, neither the load-balancing nor the inter-process communication is optimized.

Utilization of this approach can be found for example in *ParamGrid* simulator [19]. The main disadvantage of this approach is that the density of the traffic lanes in the particular rectangular pieces and the vehicle density within these lanes are not considered during the road traffic network division. These two parameters of the road traffic network can seriously affect the number of vehicles moving in the particular rectangular pieces (sub-networks) during the simulation run. Hence, the loads of the resulting sub-networks can be very different. Moreover, the number of divided traffic lanes is not considered during the road traffic network division. This can lead to a high number of divided traffic lanes and therefore to an intensive inter-process communication [3].

3.2. Optimization of the Inter-process Communication

A more advanced approach can be found in the TRANSIMS simulator [6]. The road traffic networks division used in this simulator is focused on minimization of the number of divided traffic lanes and the number of sub-networks' neighbors. Graph-partitioning methods such as orthogonal recursive bisection are used for this purpose. The lower number of neighbors and divided traffic lanes leads to a reduction of the inter-process communication.

The load-balancing of the resulting road traffic sub-networks are partially considered as well, since the total length of the traffic lanes in each sub-network is considered during the division [6]. Nevertheless, the total length of the traffic lanes is not sufficient to guarantee the load-balancing of the sub-networks due to the possible various vehicle densities in particular traffic lanes.

3.3. Static Load-Balancing

The issue mentioned in previous section is solved in the UMTSS simulator [20]. Similar to the TRANSIMS simulator, a recursive bisection method is used for the road traffic network division. However, besides the length of the traffic lanes, the vehicle densities in these lanes are considered as well. The information of the vehicle densities in the traffic lanes is estimated using the drivers' route choice decision and the origin-destination matrix [20].

Another approach focused on the load-balancing of the sub-networks can be found in the *vsim* simulator [7]. In this simulator, the number of divided traffic lanes is completely neglected. The division is performed based on the numbers of vehicles moving within the lanes of the road traffic network. This information is collected during a sequential simulation run of the distributed simulation [7].

Although this approach has the potential to produce a well load-balanced sub-networks, its main issue is the collection of the numbers of vehicles using a sequential simulation run. A sequential run of a simulation intended to be performed on a distributed computer can be difficult to perform on a single-processor computer due to the time and memory requirements [15].

4. Division Methods for Heterogeneous Clusters

The methods for the division of road traffic networks for the heterogeneous clusters are based on the methods originally developed solely for the homogenous clusters. Both the methods for the homogenous and the heterogeneous clusters are implemented in the DUTS Editor, a system for the design and division of road traffic networks developed at DSCE UWB.

We have developed two methods for the homogenous clusters. Both utilize the weights representing numbers of vehicles assigned to the particular traffic lanes for the load-balanced division of the road traffic network. Also, both methods divide the road traffic network by marking of traffic lanes, which shall be divided in order to form the required number of sub-networks. The difference between the methods is the approach used for the marking of traffic lanes. The assigning of the weights to the traffic lanes is described in Section 4.1. The division methods themselves are described in Section 4.2 and Section 4.3.

4.1. Assigning of the Weights to the Traffic Lanes

The assigning of the weights to the traffic lanes is the basis for both methods for road traffic network division for homogenous clusters. We have developed three approaches to the weights assigning (WA). All three can be used by both methods and all three utilize a road traffic simulation for counting of the vehicles moving within the particular lanes of the road traffic network. The weight of each traffic lane is then calculated as the mean number of vehicles moving within the lane during the simulation run [21]. The particular approaches to the weights assigning, which are described in following paragraphs, differ mainly in the utilized simulation.

The MaSBWA (Macroscopic-Simulation-Based Weights Assigning) approach uses a deterministic macroscopic road traffic simulation. Since there are no pseudo-random numbers utilized, all simulation runs of a single traffic network are identical. Hence, only one simulation run is required for the calculation of the weights of the traffic lanes, which makes this approach very fast [22].

The MeSBWA (Mesoscopic-Simulation-Based Weights Assigning) approach uses several simulation runs of a stochastic mesoscopic road traffic simulation based on a simple cellular automaton [21]. Because the simulation is not deterministic, several simulation runs are required in order to guarantee the fidelity of the calculated weights. This makes the MeSBWA approach slower than the MaSBWA approach [21].

Nevertheless, the far slowest approach is the MiSBWA (Microscopic-Simulation-Based Weights Assigning). The reason is the direct utilization of the microscopic simulation runs of the DUTS system (similar to the *vsim* simulator – see Section 3.2). These simulation runs have quite extreme time requirements on a standard desktop computer due to the high detail [22]. As an example, we can use a single 15-minutes-long simulation run of a road traffic network with 1 024 crossroads and over 1 200 kilometers of traffic lanes performed on an average desktop computer. Using the MiSBWA, the simulation run takes approximately 2 minutes to be performed. In comparison, the MaSBWA method requires only 6 seconds [8].

Based on the performed tests, all approaches for weights assigning give comparable results [21], [22]. Hence, it is convenient to use the fastest

approach, which is the MaSBWA. So, the MaSBWA approach is used in both road traffic network division methods for homogenous clusters by default.

4.2. MBFSMTL Method for Homogenous Clusters

As has been said, we have developed two methods for road traffic network division for homogenous cluster. The first method is the MBFSMTL (Modified Breadth-First Search Marking of Traffic Lanes), which employs a modified breadth-first searching algorithm for graph exploration [23] for the creation of the load-balanced sub-networks. The number of divided traffic lanes is partially considered as well.

The MBFSMTL method considers the road traffic network as a weighted graph with crossroads acting as nodes and the sets of lanes inter-connecting the neighboring crossroads acting as edges. This graph is then explored from a starting crossroad using the breadth-first search algorithm. The crossroads are assigned to the particular sub-networks based on the actual sum of the weights of the explored edges (i.e. sets of traffic lanes). Once the entire traffic network is explored, the lanes connecting crossroads from different sub-networks are marked to be divided [15]. The exploration of the road traffic network is depicted in Fig. 1.

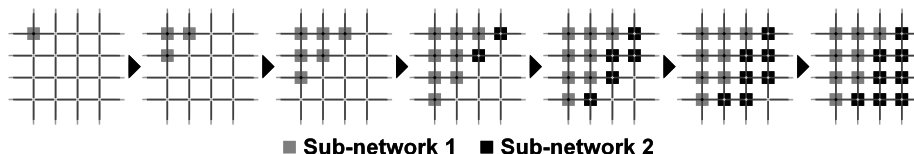


Fig. 1. The exploration of the road traffic network using MBFSMTL

Because the result of the division is significantly influenced by the selection of the starting crossroad, the entire process is performed from all crossroads of the traffic network. The division with the minimal number of divided traffic lanes is then selected [15].

4.3. GAMTL Method for Homogenous Clusters

The second method is the GAMTL (Genetic Algorithm Marking of Traffic Lanes). It employs a standard genetic algorithm for a multi-objective optimization [24] for the division of the road traffic network.

The genetic algorithms mimic the natural genetic evolution in nature. At the beginning, a set of solutions (so-called *individuals*) of the solved problem is (most often randomly) generated. This set is called *initial population*. Then, for each individual, a so-called *fitness value* is calculated using the *fitness function*. This value is an objective assessment of the individual in relation to the solved problem. The better the individual (i.e. solution of the problem) is,

the higher its fitness value is. Once this value is calculated for entire population, a number of individuals are *selected*, *crossed*, and *mutated* in order to produce a new generation. This process repeats until a preset fitness value is reached or a preset number of generations is created [25].

Using the GAMTL method, an individual is a specific assignment of the crossroads to the particular sub-networks. The fitness function represents the requirements on the solution – the load-balancing of the resulting sub-networks (called *equability*) and the minimal number of divided traffic lanes (called *compactness*). The ratio between these two parts of the fitness function can be set prior the road traffic network division similar to the number of generations and the number of mutations per individual [26]. The assignment of the crossroads to the particular sub-networks then changes using the crossover and mutation from a random pattern to clusters of crossroads (see Fig. 2).

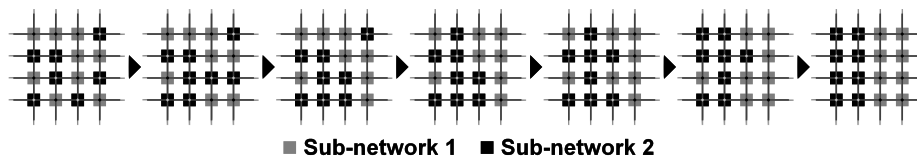


Fig. 2. The change of the assignment of the crossroads using the GAMTL

The assignment of the crossroads to the particular sub-networks represented by the individual of the last generation with the highest fitness value is used for the division of the road traffic network. Similar to the MBFSMTL method, the lanes connecting the crossroads assigned to different sub-networks are marked as divided.

Based on the performed tests, the GAMTL method gives slightly better results. This means that the distributed simulation of the road traffic network divided by the GAMTL method is slightly faster (from 3 % to 22 %) than the simulation of the same traffic network divided by the MBFSMTL method [8]. On the other hand, the computation time of the MBFSMTL method is lower than the computation time of the GAMTL method. Hence, both methods seem to be utilizable [27].

5. Division Methods for Heterogeneous Clusters

For the heterogeneous clusters, the methods originally developed for the homogenous clusters (see Section 4) must be modified.

5.1. Specifics of the Heterogeneous Cluster

The key difference of a heterogeneous cluster in comparison to a homogenous cluster is that the particular nodes have different computational

powers [28]. This makes the load-balancing of the road traffic sub-networks a little more complicated task. The division of the road traffic network into the sub-networks with similar number of vehicles (i.e. similar load) is impractical in this case [28]. Using such a division, the computational power of the slowest node would be fully utilized, but the faster nodes would have to wait for this slowest node to finish the computation in every time step.

Hence, it is necessary to take the computational power of each node of the heterogeneous cluster into the account during the road traffic network division. This means that each node is assigned by such a part of the road traffic network that the computation of one time step takes the similar time to all nodes. Then, the computational power of each node is fully utilized and the speed of the distributed simulation is maximized [27].

5.2. Necessary Modifications to the Division Methods

As mentioned in Section 5, the road traffic division methods developed for the homogenous clusters must be modified in order to be fully utilizable and efficient for the heterogeneous clusters.

Nevertheless, the assigning of the weights to traffic lanes used by both methods requires no modifications. In this computation, the data are only prepared for the marking of traffic lanes and no information about the target distributed computer it utilized. All three approaches to the weights assigning described in Section 3.1 could be used for the road traffic network division for the heterogeneous clusters. However, because all the approaches give similar results [21], [22], the fastest approach – the MaSBWA – will be used.

On the contrary, the modifications are necessary to the marking of traffic lanes of both methods. It is necessary to consider the various computational powers of the nodes of the heterogeneous cluster during the creation of the resulting sub-networks. This means that the load of the traffic network must not be divided uniformly among the resulting sub-networks, but rather in ratio, which corresponds to the ratio of the computational powers of the nodes of the cluster. However, this ratio is specific for each heterogeneous cluster and must be determined prior to the division of the road traffic network [27].

5.3. Investigation of the Speed of Heterogeneous Cluster Nodes

The determination of the computational power (i.e. speed) of the particular nodes of the heterogeneous cluster is vital for the successful division of the road traffic network. From the information about the speed of the particular nodes, the computational power ratio can be easily calculated. This ratio will be then used for the division of the load of the road traffic network among the resulting sub-networks. There are several possibilities how to determine the speed of the node [27].

The first possible approach is the utilization of known parameters of the node, such as CPU frequency, size of the RAM, number of floating-point operations per second, and so on. Nevertheless, from this information, it is difficult to determine the resulting speed of the road traffic simulation performed on the node. This information is most important for the determination of the computational power ratio of the particular nodes. Some theoretical speed of the nodes is from this point of view irrelevant [27].

Hence, it is more convenient to use a set of tests (i.e. a benchmark) for determination of the speeds of the particular nodes of the heterogeneous cluster. These tests should utilize directly the road traffic simulation in order to obtain most relevant information about the speeds of the nodes. This approach is used for both our methods for the division of road traffic network for heterogeneous clusters [27].

For the determination of the speed of each node of the heterogeneous cluster, the DUTS simulator (see Section 2.5) is used. Three road traffic networks were prepared to be performed on each node. The networks are regular grids of 16, 64, and 256 crossroads (see Fig. 3). The networks are small enough to keep the testing time in reasonable limits even on slower nodes and large enough to make the testing easily measurable [27].

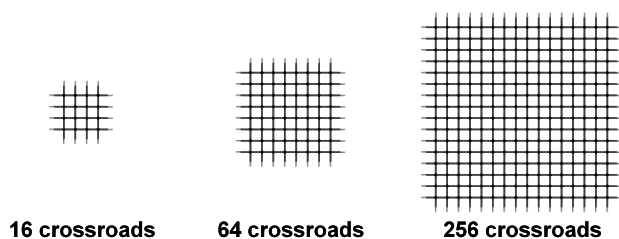


Fig. 3. The road traffic networks used for benchmarking of each node

During the benchmark, ten simulation runs of each road traffic network are performed on every node of the heterogeneous cluster. The computation time and the mean number of vehicles moving within the road traffic network are observed during each simulation run. For each road traffic network and each node, the mean computation time and the mean number of vehicles are calculated. It has been determined that ten simulation runs for each combination of the node and road traffic network are sufficient. The mean deviation of each measured value from the mean value is under 1 % for the computation time and under 3 % for the mean number of vehicles moving within the traffic network [27].

With the calculated mean computation time and mean number of vehicles for each road traffic network, the computational power coefficient for each node of the heterogeneous cluster can be determined using equation:

$$k_i = \frac{\sum_{j=1}^3 \frac{V_{ij}}{T_{ij}}}{3}, \quad (1)$$

where k_i is the computational power coefficient of the i th node, V_{ij} is the mean number of vehicles of the j th road traffic network on the i th node, and T_{ij} is the mean computation time of the j th traffic network on the i th node. Using the coefficients, the portion of the load of each node can be calculated as:

$$r_i = \frac{k_i}{\sum_{j=1}^N k_j}, \quad (2)$$

where r_i is the portion of the load of the i th node, k_i is the computational power coefficient of the i th node, k_j is the computational power coefficient of the j th node, and N is the number of nodes. The calculated portions of the load of the particular nodes are then used for division of the load of the road traffic network among the sub-networks in ratio $r_1 : r_2 : \dots : r_N$.

5.4. MBFSMTL Method for Heterogeneous Clusters

Now, as we discussed the determination of the ratio, which will be used for division of the load among the road traffic sub-networks, we can proceed with the description of the methods for marking of traffic lanes for heterogeneous clusters. Both described methods for homogeneous clusters are viable for heterogeneous clusters as well, but with some modifications. The MBFSMTL method for heterogeneous clusters is described in this section. The GAMTL method for heterogeneous clusters is described in Section 5.5.

As it was said in Section 4.2, the MBFSMTL method utilizes a modified breadth-first search algorithm. The inputs of the method are the road traffic network with traffic lanes assigned with weights (see Section 4.1 and 5.2) and the portions of the load of the particular nodes (see Section 5.3). The road traffic network is considered as a weighted graph with crossroads acting as nodes of the graph and the sets of lanes connecting crossroads acting as weighted edges of the graph (see Fig. 4). Prior to the searching of the graph, the total weight of the divided traffic network is calculated as:

$$W_T = \sum_{i=1}^L w_i, \quad (3)$$

where W_T is the total weight of the divided traffic network, L is the number of traffic lanes of the road traffic network, and w_i is the weight of the i th lane.

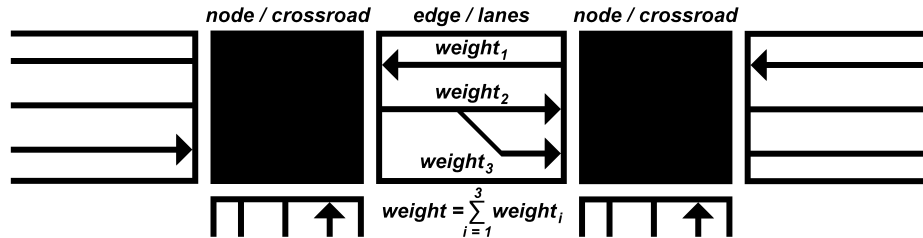


Fig. 4. Road traffic network as weighted graph (an input for division methods)

Once the total weight of the road traffic network is determined, the aimed weights of particular sub-networks can be calculated. Unlike the MBFSMTL method for homogenous clusters, this number is not the same for all sub-networks, but must be calculated using the portions of the load of the particular nodes of the heterogeneous cluster as:

$$W_{S_i} = r_i \cdot W_T, \quad (4)$$

where W_{S_i} is the aimed weight of the i th sub-network, r_i is the portion of the load of the node, on which the simulation of the i th sub-network will be performed, and W_T is the total weight of the divided traffic network. Also, the current sub-network's number is set to zero, the current sub-network's current weight is set to zero, and the aimed weight of current sub-network is set to the first value of the aimed weights of the particular sub-networks (i.e. W_{S_1}).

When all necessary values are initialized, a crossroad is selected as the starting node of the breadth-first search algorithm. The starting crossroad is assigned by the current sub-network's number (zero at this point). As the breadth-first searching is performed, the explored crossroads are assigned with the current sub-network's number and the weights of the explored edges are added to the current sub-network's current weight. When this value reaches the aimed weight of the current sub-network, the current sub-network's number is incremented, the current sub-network's current weight is reset to zero, and the aimed weight of the current sub-network is set to the next value of the aimed weights of the particular sub-networks. These steps repeat until the entire road traffic network is explored [27].

When the entire road traffic network is explored, it means that all crossroads have been assigned with the number of road traffic sub-network. To mark traffic lanes, which shall be divided to create the sub-networks, it is sufficient to mark all traffic lanes connecting all pairs of the crossroads with different numbers of sub-networks [27].

Similar to the MBFSMTL method for homogenous clusters, the breadth-first search is performed from all crossroads of the divided road traffic network. The results of the division (i.e. the sets of traffic lanes marked to be divided) are stored in the memory. When the divisions for all possible starting crossroads are finished, the division with minimal number of divided traffic lanes is selected as the result of the MBFSMTL method for heterogeneous clusters. The entire process is described in Fig. 5 using pseudo-code.

```
for (i = 0; i < nodes.count(); i++) {
    currentNumber = 0;
    currentSum = 0.0;
    setStateOfAllNodes(nodes, WHITE);
    setSubNetworkNumberOfAllNodes(nodes, 0);
    subNetworkWeight = subNetworkWeights[0];
    nodesToExplore = new Queue();
    currentNode = nodes[i];
    currentNode.state = GRAY;
    nodesToExplore.push(currentNode);
    while (!nodesToExplore.empty()) {
        currentNode = nodesToExplore.pop();
        neighbors = currentNode.neighbors();
        for (j = 0; j < neighbors.count(); j++) {
            neighbor = neighbors[j];
            if (neighbor.node.state == WHITE) {
                neighbor.node.state = GRAY;
                nodesToExplore.push(neighbor.node);
                currentSum += neighbor.weight;
            }
        }
        currentNode.state = BLACK;
        currentNode.subNetworkNumber = currentNumber;
        if (currentSum > subNetworkWeight) {
            currentNumber++;
            currentSum = 0;
            subNetworkWeight = subNetworkWeights[currentNumber];
        }
    }
    divisions[i] = storeCurrentDivision(nodes);
}
bestDivision = findBestDivision(divisions);
```

Fig. 5. The algorithm of the MBFSMTL method for heterogeneous clusters

5.5. GAMTL Method for Heterogeneous Clusters

As it was said in Section 4.3, the GAMTL method utilizes a genetic algorithm. Similar to the MBFSMTL method, the GAMTL method utilizes the road traffic network with traffic lanes assigned with weights and the portions of the load of the particular nodes as its inputs.

Similar to the GAMTL method for homogenous clusters, each individual is represented by a vector of integer values with length corresponding to the total number of crossroads K . Each individual corresponds to a single assignment of the crossroads to the particular sub-networks (see example for two sub-networks depicted in Fig. 6). The initial population of 90 individual is randomly generated. This means that, in each individual, the crossroads are randomly assigned to the particular sub-networks.



Fig. 6. An individual with corresponding assignment of the crossroads

Once the initial population is generated, the fitness function is calculated for each individual. Similar to the homogenous GAMLT method, the fitness functions consists of two parts – the *compactness* and the *equability*.

The compactness is used for minimization of the number of divided lanes. It can be calculated as:

$$C = \frac{L - L_D}{L}, \tag{5}$$

where C is the compactness, L_D is total number of divided lanes, and L is the total number of lanes. The compactness is calculated in the same way for both heterogeneous and homogenous clusters.

The only part of the GAMTL method, which is different for the heterogeneous clusters, is the calculation of the equability, which is used for correct distribution of the load among the sub-networks. For the heterogeneous clusters, the load of the road traffic network cannot be divided uniformly, but rather using the portions of the load of the particular nodes. Hence, the equability can be calculated as:

$$E = 1 - \frac{\sum_{i=1}^M \frac{\left| r_i - \frac{W_{Si}}{W_T} \right|}{\max\left(r_i, \frac{W_{Si}}{W_T}\right)}}{M}, \tag{6}$$

where E is the equability, W_{Si} is the total weight of the i th sub-network using the assignment of the crossroads corresponding to the individual, for which the equability is calculated, W_T is the total weight of the road traffic network (see Equation (3)), M is the number of sub-networks, and r_i is the portion of the load of the node, on which the simulation of the i th sub-network will be performed.

With both compactness and equability calculated, it is possible to calculate the entire fitness function as:

$$F = r_E \cdot E + (1 - r_E) \cdot C, \tag{7}$$

where F is the fitness function, C is the compactness, E is the equability and r_E is the ratio of the equability, which can be set in range $(0, 1)$.

The r_E determines the preference of the compactness (optimization of the inter-process communication) or the equability (load-balancing of the sub-networks). For r_E equal to 0, the GAMTL method is focused solely on the compactness. So, the division with minimal number of divided lanes is found. However, the minimal possible number of divided lanes is zero, which happens in case that there is only one resulting sub-network (i.e. the traffic network is not divided at all). Since such a division is useless for our purposes, the r_E should be greater than 0. For r_E equal to 1, the GAMTL method is focused solely on the load-balancing and the number of divided lanes is not taken into account. This setting is theoretically usable, because the required number of sub-networks is created. Nevertheless, a very high number of divided lanes is generated, because there is no component of the fitness function, which would prevent it. Hence, an intense inter-process communication and consequently a non-negligible reduction of the speed of the distributed simulation must be expected. Based on preliminary experiments with the settings of the r_E , the default value is set to 0.25. With this setting, the number of divided traffic lanes is sufficiently low for many instances and the resulting sub-networks are still well load-balanced.

Once the fitness function is calculated for all 90 individuals, ten individuals with highest fitness function are selected for crossover using pairs of selected individuals. Each combination of two parent individuals produces two offspring (see Fig. 7). The first offspring receives integer values of even indices from the first parent and integer values of odd indices from the second parent. The second offspring receives all remaining values from both parents.

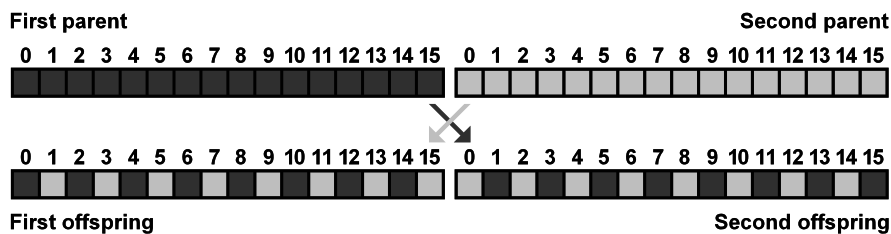


Fig. 7. The crossover of two parent individuals producing two offspring

The combination of all selected individuals produces a new generation of 90 individual. Each individual can be mutated. The mutation is limited to the maximum of five mutations per individual, which means that up to five values of each individual of the new generation can be randomly changed. Then, the fitness value is calculated for all individuals and the process repeats for 10 000 generations. All parameters of the GAMTL method for heterogeneous clusters (number of generations, number of individual, r_E , etc.) were adopted from the GAMTL method for homogenous clusters. There, the parameters were set based on preliminary testing of the method.

Once the genetic algorithm is completed, the traffic lanes connecting crossroads assigned to different sub-networks are marked as divided, similar to the MBFSMTL method.

6. Tests and Results

Both described methods for heterogeneous clusters have been thoroughly tested. There were two sets of tests. The first set of tests (see Section 6.2) was the benchmark of the heterogeneous cluster, on which the distributed road traffic simulation was tested (see Section 5.3). This benchmark was performed prior the division of the road traffic networks, since its result (portions of the load) is a necessary input for both division methods for heterogeneous clusters. In the second set of tests (see Section 6.3), both division methods for heterogeneous clusters were tested and compared to their counterparts for homogenous clusters.

6.1. Heterogeneous Cluster Used for Testing

Both sets of tests were performed on a heterogeneous cluster consisting of nine nodes. Eight nodes were used as working nodes performing simulation of particular road traffic sub-networks. The remaining (control) node served as a centralized barrier for the synchronization of the working processes (see Section 2.4). The parameters are summarized in Table 1.

Table 1. Parameters of the nodes of the distributed cluster for testing

No.	Type	CPU	RAM [MB]	OS
1	Working	Intel Celeron 1.70 GHz	504	WinXP SP3
2	Working	Intel Pentium D 3.6 GHz	512	Debian 5.0.1
3	Working	Intel Xeon 3.2 GHz	2048	Debian 5.0.1
4	Working	Intel Core 2 DUO 2.66 GHz	4096	WinXP SP3
5	Working	Intel Core i5-2400S 2.5 GHz	8192	Win7 64 bit
6	Working	Intel Xeon 3.2 GHz	2048	Debian 5.0.1
7	Working	Intel Xeon 3.2 GHz	2048	Debian 5.0.1
8	Working	Intel Pentium D 3.6 GHz	512	Debian 5.0.1
9	Control	Intel Xeon 3.2 GHz	2048	Debian 5.0.1

6.2. Benchmark of the Working Nodes of the Heterogeneous Cluster

The benchmark of the particular working nodes of the heterogeneous cluster was performed following the instructions described in Section 5.3. So, the results of the benchmark are the portions of the load of the particular nodes. In order to test the road traffic network division for various numbers of sub-

networks, various numbers (two, four, and eight) of working nodes were used (see Section 6.3). Hence, the portions of the load were calculated for two working nodes (working nodes 1-2, control node 9), four working nodes (working nodes 1-4, control node 9), and eight working nodes (working nodes 1-8, control node 9).

The benchmark was performed as follows. Sequential simulations of three road traffic networks (see Fig. 3) were performed ten times on each working node. Each simulation run was 900 time steps (corresponding to 15 minutes of the real time) long. Two values were observed in every simulation run – the mean number of vehicles moving within the road traffic network and the computation time of the simulation run. The computation times and the mean numbers of vehicles collected during ten simulation runs were then averaged and are summarized in Table 2 and Table 3, respectively.

As can be seen in Table 2, there are significant differences of the computation times of the same road traffic network simulated on different nodes. It can be observed that the computation time is not linearly dependent on the CPU frequency. Nevertheless, the results are consistent with the anticipated computational power of the particular nodes.

Table 2. The mean computation times of the simulation runs

	Number of crossroads of traffic network		
	16	64	256
Node No.	Computation time [ms]		
1	6 952	25 449	98 386
2	3 082	12 808	48 145
3	4 294	16 726	62 620
4	1 658	7 466	27 492
5	1 095	4 664	18 017
6	4 274	16 728	62 563
7	4 286	16 746	62 618
8	3 106	12 806	48 153

Lastly, it should be noted that the values for nodes 2 and 8 are very similar and the values for nodes 3, 6, and 7 are very similar as well. This is not a coincidence. The nodes 2 and 8 and the nodes 3, 6, and 7 are computers with identical parameters. So, it could be assumed that the results of the benchmark will be the same for all identical nodes. Nevertheless, in order to verify this assumption, the benchmark was performed on all nodes. This way, it was shown that the results for nodes 2 and 8 are nearly identical and the results for nodes 3, 6, and 7 are nearly identical as well (see Table 2). The maximal difference is less than 1 %.

As can be seen in Table 3, the mean number of vehicles moving within the road traffic network is not influenced by the node, on which the road traffic network is simulated. This is an expected and required behavior, since the road traffic simulation should give the same results regardless the computer, on which it is performed. The negligible differences of the particular values in

one column are caused by the stochastic nature of the simulation. Due to this nature, even two simulation runs of the same road traffic network performed on the same node are slightly different.

Table 3. The mean number of vehicles of the simulation runs

	Number of crossroads of traffic network		
	16	64	256
Node No.	Mean number of vehicles during simulation run		
1	724	1 660	3 514
2	721	1 636	3 585
3	726	1 647	3 585
4	720	1 684	3 514
5	718	1 666	3 535
6	727	1 649	3 580
7	723	1 652	3 593
8	717	1 641	3 581

Based on the obtained values, the computational power coefficients and the portions of the load of each node for two, four, and eight utilized working nodes can be calculated using the Equation (1) and Equation (2), respectively. The results are summarized in Table 4. The portions of the load of the particular nodes were used as the input for both division methods for heterogeneous clusters.

Table 4. Computational power coefficients and portions of the load

Nodes count	Node No.	Computational power coefficient	Portion of the load
2	1	0.0684	0.3199
	2	0.1454	0.6801
4	1	0.0684	0.1170
	2	0.1454	0.2487
	3	0.1083	0.1853
	4	0.2625	0.4491
8	1	0.0684	0.0507
	2	0.1454	0.1078
	3	0.1083	0.0803
	4	0.2625	0.1946
	5	0.4032	0.2989
	6	0.1086	0.0805
	7	0.1083	0.0802
	8	0.1444	0.1071

6.3. Performance of the Methods for Heterogeneous Clusters

The performances of the MBFSMTL and GAMTL methods for heterogeneous clusters were tested and compared to the performances of the MBFSMTL and GAMTL methods for homogenous clusters. Using this approach, it is shown that the consideration of the computational power of particular nodes of the heterogeneous cluster during the road traffic network division influences the resulting speed of the distributed road traffic simulation.

For the testing, four road traffic networks were used. Network 1 was an irregular road traffic network of 55 crossroads inspired by the Bory district of the Pilsen city, Czech Republic. Networks 2, 3, and 4 were regular square grids of 64, 256, and 1 024 crossroads, respectively. The networks were divided into two, four, and eight sub-networks using both methods for heterogeneous clusters and both methods for homogenous clusters. Then, the distributed microscopic road traffic simulation using the DUTS system was performed on two, four, and eight working nodes of the heterogeneous cluster (see Section 6.1), respectively.

For each combination of the divided road traffic network, the number of sub-networks, and the division method, ten simulation runs were performed and the computation time and the numbers of vehicles moving in particular sub-networks were observed. Similar to the benchmark, each simulation run was 900 time steps long, which corresponds to 15 minutes of the real time. This length of the simulation runs was selected, because the real data of the road traffic intensities in Pilsen city are collected in 15-minutes-long intervals. This enables an easier comparison of the results from the simulation with the real measured data in the future [27].

The averaged numbers of vehicles moving in particular sub-networks were used for investigation of the distribution of the total load among the particular sub-networks in the distributed road traffic simulation. The portions of the load of the particular sub-networks are compared to the intended values obtained from the benchmark (see Table 5 for the MBFSMTL and Table 6 for the GAMTL method).

As can be seen in Table 5 and Table 6, the real portions of the load of the particular sub-networks are similar (but not identical) to the intended values regardless the utilized division method. The mean differences between the intended and real portions are low for both methods – 8.5 % for the MBFSMTL method and 9.3 % for the GAMTL method. Hence, from this point of view, both methods give similar results. The reason for the observed differences between intended and real portions of the load is that the methods are not focused solely on load-balancing, but on the number of divided traffic lanes as well. Hence, both methods can produce a division, in which the load-balancing is not perfect, but the number of divided traffic lanes is low.

The averaged computation times of the distributed road traffic simulation are summarized in Table 7. As can be seen, both methods for heterogeneous clusters give better results (i.e. lower computation time of distributed simulation run) than both methods for homogenous clusters. The savings

vary from 3 % to 50 %. Such a high variance can be observed, because the total computation time of the distributed simulation is not influenced solely by the load-balancing, but by the inter-process communication as well.

Table 5. Portions of load of particular sub-networks created by MBFSMTL method

MBFSMTL method			Number of crossroads			
Nodes count	Node No.	Intended portion	55	64	256	1 024
			Portions of the load			
2	1	0.3199	0.2786	0.2521	0.2655	0.2513
	2	0.6801	0.7134	0.7679	0.7345	0.7487
4	1	0.1170	0.1376	0.0989	0.0991	0.1084
	2	0.2487	0.2218	0.2547	0.2669	0.2391
	3	0.1853	0.1950	0.2001	0.1741	0.1719
	4	0.4491	0.4456	0.4463	0.4599	0.4806
8	1	0.0507	0.0411	0.0551	0.0599	0.0479
	2	0.1078	0.1112	0.1189	0.0996	0.0981
	3	0.0803	0.0901	0.0761	0.0813	0.0816
	4	0.1946	0.2139	0.2144	0.2034	0.2017
	5	0.2989	0.2782	0.3007	0.3001	0.2916
	6	0.0805	0.0751	0.0697	0.0911	0.0722
	7	0.0802	0.0791	0.0718	0.0765	0.0709
	8	0.1071	0.1113	0.0933	0.0881	0.1360

Table 6. Portions of load of particular sub-networks created by GAMTL method

GAMTL method			Number of crossroads			
Nodes count	Node No.	Intended portion	55	64	256	1 024
			Portions of the load			
2	1	0.3199	0.3491	0.2992	0.2799	0.2751
	2	0.6801	0.6509	0.7008	0.7201	0.7249
4	1	0.1170	0.1118	0.1203	0.1021	0.0977
	2	0.2487	0.2193	0.2409	0.2764	0.2189
	3	0.1853	0.1604	0.2130	0.1919	0.2044
	4	0.4491	0.5085	0.4258	0.4296	0.4790
8	1	0.0507	0.0391	0.0611	0.0626	0.0433
	2	0.1078	0.0961	0.1109	0.1089	0.1189
	3	0.0803	0.0902	0.0727	0.0894	0.0788
	4	0.1946	0.2005	0.2011	0.2107	0.2119
	5	0.2989	0.2501	0.3107	0.2856	0.2999
	6	0.0805	0.1055	0.0788	0.0765	0.0911
	7	0.0802	0.0917	0.0809	0.0719	0.0688
	8	0.1071	0.1268	0.0838	0.0944	0.0873

The inter-process communication highly depends on the number of divided traffic lanes and this number varies significantly depending on the divided

road traffic network and the utilized division method. The numbers of divided traffic lanes are summarized in Table 8.

Table 7. Mean computation time of the simulation run

Nodes count	Crossroads count	Computation time [s]			
		Homogenous		Heterogeneous	
		MBFSMTL	GAMTL	MBFSMTL	GAMTL
2	55	29.7	25.5	22.9	21.1
	64	32.9	24.8	23.0	21.8
	256	66.3	66.5	58.3	54.2
	1 024	207.0	216.8	193.2	197.9
4	55	15.7	12.4	9.7	8.9
	64	19.0	12.1	11.5	9.5
	256	25.1	27.9	21.2	19.7
	1 024	76.9	96.6	72.6	74.0
8	55	8.9	8.1	6.3	6.0
	64	10.1	8.4	6.4	5.2
	256	16.2	16.9	13.2	12.5
	1 024	49.5	56.9	42.1	47.7

Table 8. Numbers of divided traffic lanes

Nodes count	Crossroads count	Number of divided traffic lanes			
		Homogenous		Heterogeneous	
		MBFSMTL	GAMTL	MBFSMTL	GAMTL
2	55	27	21	14	16
	64	44	16	16	18
	256	44	80	28	54
	1 024	108	196	82	144
4	55	70	30	63	27
	64	100	32	81	32
	256	170	142	134	108
	1 024	280	794	210	706
8	55	94	67	79	65
	64	144	116	98	80
	256	322	576	360	498
	1 024	592	1 112	588	996

From Table 8, it is clear that the GAMTL method for both homogenous and heterogeneous clusters generate a high number of divided traffic lanes for larger traffic networks (network 3 – 256 crossroads and network 4 – 1 024 crossroads). The reason for this is that, for a high number of crossroads, the genetic algorithm of the GAMTL method is unable to reach optimal division within the preset number of generations (i.e. 10 000 generations). So, the crossroads assigned to the particular sub-networks are not sufficiently clustered together. Consequently, many crossroads has crossroads from

different sub-networks as their neighbors. This greatly increases the number of divided traffic lanes and affects the resulting computation time of the distributed simulation.

In order to investigate this behavior further, another set of tests was performed. Two largest traffic networks (network 3 – 256 crossroads and network 4 – 1 024 crossroads) were divided into four sub-networks using the heterogeneous GAMTL method with 10 000, 100 000, and 1 000 000 generations, respectively. The best achieved compactness, equability, and fitness value, the computation time necessary for the division, and the numbers of divided traffic lanes were observed during the division. The division was performed on the node 4 of the heterogeneous cluster (see Table 1 for parameters). Then, the distributed road traffic simulation of the four resulting sub-networks was performed ten times for each combination of the network and the number of generations on working nodes 1 to 4 and control node 9 (see Table 1 for parameters) and the mean computation time was determined. The results are summarized in Table 9.

As can be seen in Table 9, the best achieved compactness, equability, and fitness value increase with increasing number of generations. Consequently, the quality of division is improving with increasing number of generations. This means that the number of divided traffic lanes is lower (corresponds to compactness) and the resulting sub-networks are better load-balanced (corresponds to equability). Nevertheless, this improvement is minimal (see last two rows of Table 9) and for the price of significant increase of computation time necessary for road traffic network division (see sixth row of Table 9).

Table 9. Dependency of the heterogeneous GAMTL method on the generations count

Crossroads	256			1 024		
	10^4	10^5	10^6	10^4	10^5	10^6
Compactness	0.9007	0.9136	0.9265	0.8329	0.8381	0.8542
Equability	0.5777	0.7289	0.7445	0.7575	0.7615	0.7973
Fitness	0.8200	0.8674	0.8810	0.8150	0.8179	0.8310
Division time [s]	46.2	422.1	4 159.1	180.8	1 699.0	15 795.0
Divided lanes	108	94	80	706	684	616
Simulation time [s]	19.7	19.6	19.3	74.0	73.8	73.4

This slow increase of the quality of division corresponds to the result of the testing of the GAMTL method for homogenous clusters (see [29]). However, a better result could be expected from both homogenous and heterogeneous versions of the GAMTL method. The reason for the slow increase of the quality of division is probably suboptimal settings of the parameters of the utilized genetic algorithm. The most obvious parameters are the number of individuals in a generation, number of selected individuals from each generation, number of mutations, and the value of the r_E . These parameters

were set using preliminary testing of the homogenous GAMTL method and were adopted by the heterogeneous version. The preliminary testing suggested that the setting was convenient. Nevertheless, for optimal settings, a more thorough testing of all combinations of the particular parameters would be required. Moreover, there are other features of the genetic algorithm, which can be also very important (e.g. type of crossover, type of selection, etc.). These features have not been investigated yet.

The optimal settings of all mentioned parameters and features of the genetic algorithm of the GAMTL method is outside the scope of this paper. Nevertheless, it is one of the main aims of our future work. More information can be found in [30].

7. Conclusions

In this paper, we have described two methods for division of road traffic networks for heterogeneous clusters – the MBFSMTL and the GAMTL. Both these methods are based on their counterparts originally designed for homogenous clusters. The methods for heterogeneous clusters divide the load among the particular road traffic sub-networks using a ratio based on the computational powers of the particular nodes of the heterogeneous cluster. In order to calculate the ratio, all nodes of the target heterogeneous cluster are investigated for their computational powers using a benchmark test.

The performances of both methods for heterogeneous clusters were thoroughly tested and compared mutually and with their counterparts for homogenous clusters. Both methods for heterogeneous clusters showed better results than both methods for homogenous clusters for all tested instances. The savings of the computational time of the distributed simulation reached up to 50 %. Hence, it is clear that the adaptation of the load of particular sub-networks for the computational power of the nodes has a significant effect on the resulting computation time of the distributed simulation.

When both methods for heterogeneous clusters are compared together, the GAMTL method gives better results for smaller road traffic networks than the MBFSMTL methods. On the contrary, the MBFSMTL method gives better results for larger traffic networks, and shows more stable results due to the lower number of divided traffic lanes. At first glance, this makes the MBFSMTL method more utilizable than the GAMTL method. However, the worse results of the GAMTL method could be caused by suboptimal settings of the parameters of the utilized genetic algorithm. So, it is possible that, after an optimization, the GAMTL method will give better results than the MBFSMTL method.

In our future work, we will first focus on the optimization of the GAMTL method for both homogenous and heterogeneous clusters in order to achieve lower number of divided traffic lanes even for large traffic networks.

Another step in our research is the combination of the described methods for the load-balanced division of road traffic networks with efficient communication protocols. For the testing of the division methods described in this paper, a basic (i.e. not optimized) communication protocol was used. However, we have developed several advanced communication protocols, which can significantly reduce the amount of inter-process communication [3]. Since the inter-process communication is relatively slow, the utilization of an advanced communication protocol can significantly improve the overall performance of the distributed road traffic simulation. Moreover, some of the advanced protocols could mitigate the higher number of divided traffic lanes produced by the division methods in some instances [3].

Another promising direction of our research is the parallel/distributed road traffic simulation, which can better exploit the computational powers of the nodes with multiple or multi-core processors than a pure distributed simulation due to the utilization of shared memory instead of message passing were possible [12].

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