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KALIBRACE VYSOKORYCHLOSTNÍ MIKROSIMULACE DOPRAVY

CALIBRATION OF THE HIGH-SPEED TRAFFIC MICROSIMULATION

ROZŠÍŘENÝ ABSTRAKT DIZERTAČNÍ PRÁCE
EXTENDED ABSTRACT OF A PHD THESIS

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Contents

Chapter 1

Introduction

This chapter starts with the motivation for the whole research presented in the thesis. Then, the research area and objectives of the thesis are formulated. An outline of the thesis is given at the end of the chapter.

1.1 Motivation

A modern world without cars or road transport in general is something we are simply unable to imagine. Cars affect everyone on a daily basis and many industries are strongly dependent upon them.

The history of modern road transport, or more specifically vehicles with combustion engines, dates back to the end of the 19th century. Modern cars developed from the era of self-propelled carriages propelled by steam engines. The cars were initially utilized by individuals or small groups of fans, while the masses simply didn't believe or even accept the concept at that time. The society began to change their attitude over time and thanks to persons such as *Karl Benz, Gottlieb Daimler, Wilhelm Maybach, Armand Peugeot* and *Henry Ford*, the car soon became engrained as an integral part of everyday life [29].

Road transport has brought forward an acute need for rules as the cars were growing in popularity. This was the impetus for creating the first road traffic regulations and laws. Then it became necessary to manage traffic at the busiest road connections – at the crossroads. The police initially took responsibility for this task, but were later replaced by light signals and other automated traffic control systems. Road transport today continues to develop dynamically. The latest technologies are developed and deployed, in the areas of transport infrastructure, navigation systems and traffic management and even in cars themselves. All these aspects are integrated under a notion of *Intelligent Transportation Systems*, or *ITS*. These systems monitor road traffic to a fine level of detail and can even intervene when needed.

The number of vehicles continues to grow in all segments, including both passenger cars and trucks or other types of vehicles. Technological advances have been the primary driver of such an increase and have resulted in safer and less expensive vehicles that are now available to a larger group of people. The car ownership is now the standard in advanced countries. However, the number of vehicles continues to rise at a rate that is much faster than the pace at which existing roads are expanded or new roads are built. While the overall road network has only been expanded by a few kilometres per year (there were a total of 55,747.6 km of roads in the Czech Republic in 2014, an increase of only 240 km over

2005), the number of cars has increased by nearly 25% over the same period of time (again in comparison with 2005, with 4.83 million registered cars in 2014) [26]. Investments into transport infrastructure also continue to drop year-on-year, with the amount invested in 2014 only 40% (less than half) of the amount invested in 2005. Conversely, costs continue to rise for the road network repairs and maintenance due to the need to maintain older roads as they age [30].

This situation results in an unfortunate increase in road traffic density, which has an impact on transport itself. The denser traffic increases the probability of accidents and other collisions while the busiest areas of roads and crossroads suffer from gridlock and congestion [1, 21]. This phenomenon is regularly occurring at some locations and is a daily problem.

Secondary problems also co-exist. The cars stuck in long traffic jams move slowly, wasting fuel and spewing large amounts of polluting exhaust gases into the atmosphere [7]. These contain hazardous substances including carbon dioxide and nitrous oxides that have a negative environmental impact. There are also economic consequences. Traffic, which causes delays, thereby results in an overall increase in transport costs. Last but not least, congestion actually extends the time needed to transport people. All these aspects have mobilised countries to organise and make greater efforts to find solutions to the current problems faced by transport. These issues can be resolved in three ways in a general sense:

(a) mitigating the negative impacts of transport,

(b) media campaigns and official regulations, and

(c) modernisation and the construction of new roads and/or vehicles.

While efforts to mitigate the negative impacts of transport (a) have begun to bear fruits recently, for instance, modern technology has been applied to vehicles to ensure they comply with standards [28], the same cannot be said about media campaigns and official regulations (b). Media campaigns and official regulations seek to convince and even force the general public to act in a more ecological and efficient manner when it comes to transport. This primarily involves media campaigns in support of public transport. Recent statistics actually show a decrease in the number of public transport passengers, while nearly all of those public transport passengers have moved to personal cars [26, 30]. The final measure (c) could be of assistance in light of the current situation where excessively high road traffic density is responsible for traffic congestion to a large extent. Modernisation and construction of new roads is much more financially intensive and is not always acceptable. The open space needed to build or expand roads is not often available. The new construction would lead to additional devastation of the countryside in many rural areas. The inadequacy of this solution is confirmed by the fact that financing for transport infrastructure continues to drop [26]. The situation is better in the case of construction of new vehicles. These are nowadays integrated with modern communication features known as *Vehicle-to-infrastructure (V2I)*, *Infrastructure-to-vehicle (I2V)* and/or *Vehicle-to-vehicle (V2V)* that can perhaps help to avoid some kind of collisions. However, such a technology is only in its early adoption stages.

1.2 Research Area

There is another way to efficiently increase the network capacity without constructing new roads. Detailed traffic analysis conducted on a specific road segment may generate an optimum traffic control strategy that increases the capacity and decreases the traffic density [38, 4, 21]. The gradual integration of a number of roads, cities and towns may eventually drive the optimisation of the entire transport network in a city, district or region. The optimisation includes many targets such as modifying speed limits, changing rules with respect to the right-of-way, modifying the timing at crossroads, implementing dedicated lanes of travel and much more. And not only the static or permanent optimisations, but also adaptive changes during operations are possible by the deployment of modern ITS (traffic reports, roadway information signs, portable signs, etc.). This means using different configurations (e.g. speed limits noted above) to adapt a specific road segment to different needs at different times. This dynamic road traffic management can be seen, for example, in the article from 2013 [11].

Moreover, road traffic analysis tools can be also utilized in so-called *Advanced Traveller Information Systems - ADT* (e.g. online traffic applications used in smartphones and other portable devices). This tools can help drivers to make the decision making process significantly easier on the basis of their own knowledge and the information provided from such systems. Drivers informed, e.g. about collisions, may decide to bypass a critical place when there is still time to do it and thus avoid additional traffic problems. Overview of such systems can be found in the separate article from 2015 [36].

Road traffic simulators are used to assist in the decision making process when selecting a specific strategy. Two fundamental prerequisites are critical with respect to traffic simulators used for these purposes. The first is that the simulator must be able to simulate the given road section at a speed that is faster than real time for the needs of forecasting. Sometimes the simulations must be conducted at a much faster speed to test a number of optimisation strategies and identify the best solution in a real time. The second and clearly logical prerequisite is that such a simulator must be very accurate. Both these prerequisites, however, counterbalance one another. More accurate simulators are capable of modeling traffic at a detailed microscopic level (see below). These simulators define very detailed relationships between the individual entities involved in transport. As there are many such entities, these simulators are very demanding in terms of computing resources.

Every simulation model must be calibrated (and validated) against relevant data, ideally the data coming from the specific road section, before its deployment in the real world. A problem may occur with respect to transport where the data is not available at the required level. Such situation occurs when monitoring sensors used to generate the data are not available for the given road section. Another problem connected with the use of the real data is that despite deploying suitable sensors, the resulting data samples may be lacking or missing for a specific period of time. Inclement weather (camera fogging, etc.) or a simple hardware or software fault in the sensor may be responsible for such a situation.

1.3 Research Objectives

The main research objective for the thesis is to

„develop a fast and accurate traffic simulator, capable of multi-real-time simulations of complex traffic areas.“

As indicated, such a simulator must meet two basic requirements. It must be able to perform simulations faster than in real time. Moreover, it must be able to do multiple in real time simulations due to the necessity of various road traffic scenarios simulation.

The second requirement is that it must be very precise, e.g. the accuracy should be better than current state of the art. Finally, its calibration must be supported for several traffic facilities and different traffic data as they occur in the real world (e.g. the operation with missing data has to be supported).

The main research objective can then be re-formulated in several sub-goals. The first sub-goal is *to find a proper road traffic simulation model* and *to develop a basic version of a simulator based on the chosen model.* Then, it will be needed *to accelerate the simulator* in the case it is too slow and unable to perform the multiple in real time simulations. For the quality assurance, *a calibration methodology needs to be proposed and evaluated*, not only on macroscopic data, but also on microscopic data sets. For a real deployment of the road traffic simulator, *a methodology has to be developed to deal with incomplete field data sets.*

1.4 Thesis Outline

The thesis is composed as a collection of papers. The research contribution of the thesis is thus constituted by the five peer-reviewed research papers, in their original publication format. The thesis is organised as follows: Chapter 1 (this chapter) gives an introduction to the thesis. Chapter 2 surveys the state of the art, and presents relevant background information for the research. Chapter 3 summarises the research process and gives an overview over the papers constituting the research contribution. And finally, Chapter 4 presents conclusions and proposes future research directions.

Chapter 2

Survey of the State of the Art

This chapter surveys the state of the art and gives the relevant background information needed for a proper understanding of the work presented in the thesis.

2.1 Road Traffic Simulation

A road traffic simulation model represents a highly dynamic system, where the time constitutes a primary independent variable. In general, simulation models describe how each entity of a system reacts to stimuli and thus develops its state in time. Discrete simulation models are representative of real-world systems in such a way that the conditions suddenly change right at designated time points. There are two types of these models [25, 33, 5]. Models with a discrete time divide the time into intervals of a fixed length. These models calculate an activity in each interval (e.g. for vehicle acceleration, deceleration) that changes the state of an entity. On the other hand, some systems don't activate the entities until the moment when their actual change of the state is planned. Here we speak about models with discrete events where the events are triggered.

Due to the fact that this event triggering can effectively be scheduled, it is possible to save computing power. However, it does not apply to traffic simulators, because the number of triggered events is always high. Microscopic and macroscopic models are basic road traffic simulation models. They are described in detail in next sections.

2.1.1 Microscopic Models

Microscopic traffic models describe each entity and each interaction individually. For every vehicle in the road network, it is separately calculated how it will behave in the following step on the basis of the surrounding conditions. As these models deal with every vehicle on the road section, they manage to be very accurate.

Many of the microscopic parameters can be obtained by monitoring real traffic conditions. For example, two aerial images of the same area taken successively can give us the position, speed and various intervals. More feasible sources of information are, compared to aerial images, inductive detectors and detection cameras. For example, by using inductive detectors placed on the roads, it is possible to obtain velocity, space, and with the cooperation of detection cameras, the length of vehicle can be recognized. Moreover, it is possible to obtain headways (i.e. travel time for every vehicle) using (at least) two detection cameras with a vehicle plate recognition feature integrated. Such cameras have to be placed at the beginning and the end of the monitored segment.

Roughly a decade ago there was a huge increase of interest in the traffic models, which looked at the traffic situation on the microscopic level [3]. This was mainly due to the increase in the processing power of personal computers, which enabled performing microscopic simulation in a quite reasonable time. Currently, there are many microsimulation transport tools: from small, educational programs, where the entry and exit into the simulator is commonly obtained via the command line, to academic projects and commercial simulators. These latter ones are often based on successful academic projects, and have, among other things, also a greatly reworked graphic user interface. Examples of traffic microsimulators include (without reference) *AIMSUN, CORSIM, DRACULA, FREESIM, HUTSIM, INTEGRATION, MITSIM, NETSIM, PADSIM, PAMINA, PARAMICS, SITRAS, TRANSIMS* or *VISSIM*. More details regarding the microsimulation models can be found in specialized literature (e.g. [3, 20, 47]).

There are models (called *submicroscopic*) that try to model the reasons for which individual simulated entities change their behavior. These may be the breaking performance, engine speed, speed of gear-change, and many others. Some of the above mentioned models are complemented by such submicroscopic properties. Therefore, these models require even more time for the simulation than the pure microscopic ones.

2.1.2 Macroscopic Models

Macroscopic models describe traffic on a very high level with just a few equations [47]. Instead of individual entities, aggregated values are modeled and, therefore, we are not interested in vehicles as separate entities. The macroscopic level of description of traffic is a dynamic description of the entire monitored section and is designated especially for strategic purposes (planning new roads, etc.). Macroscopic variables are always analyzed over a particular area of interest. This area (or even interval) means a certain space in the graph of trajectories. It is possible to define three such areas, along their characteristic variables.

On the border of microscopic and macroscopic traffic simulation models, mesoscopic ones can also be found. They analyze traffic at the level of small groups of vehicles, but not at the level of individual vehicles (as it is with microscopic ones) or the whole road section (as it is with macroscopic ones).

2.1.3 Other Properties

Some traffic simulators do not include any random components and, therefore, each entity is modeled using an exact relationship expressed by mathematical equations. Such a model becomes deterministic. Conversely, models that contain a random component are called probabilistic traffic models. Some actions in these models take place with a certain probability and the resulting behavior is therefore not possible to determine as precisely as with the models of the previous type. Probabilistic models are useful in the case where we do not have a detailed information about the modeled area or even when we cannot find out all the information from modeling entities.

Another way the traffic simulation models can be categorized is according to the geographical scope of the model. Some models are intended only for specific purposes, for example, for the analysis of the utilization of a particular intersection, or a particular roundabout. Their impact is, therefore, local. Other models are instead focused on a wider area and they even analyze whole towns. It is evident that for the simulation models capturing more extensive road sections, performance problems appear on account of a greater number of modeled entities. On the other hand, modeling a larger area is usually preferred to get a better overview of the traffic.

Finally, traffic simulators also differ with respect to entities they model (in the case of microsimulation models). Most simulators are devoted to personal or commercial vehicles. However, it is also possible to meet with specific simulators which include pedestrians, cyclists and other entities in their models. The simulation model then becomes very complicated as well as the requirements for computing resources are increasing.

2.1.4 Quality of Simulation Models

Any simulation model must be calibrated prior to its deployment and usage. Model calibration can be defined as a process in which the input parameter values are being tuned in order to reflect modeled traffic conditions at required level of precision. A common practice is to utilize a real data obtained directly from the modeled sections [3, 20, 47]. A close attention to this process is needed in order to perform it correctly [2]. Many guidelines have been created by international authorities [17] and other entities for these purposes [18, 45]. However, since it is not always possible to get a real data, *traffic fundamental diagrams* are often used for the process of calibration. These diagrams are reflecting the traffic fundamental equation.

Greenshield was the first, who in 1934 came up with a formulation of mathematical relationships between traffic variables. As the original formulation was based on a very small sample of data, the model was too oversimplified [46]. It has been shown that some of the relationships in his fundamental diagram do not correspond to reality. Despite this fact, this model is still used for the traffic simulation models calibration and/or validation because of its simplicity. *Pipes* came up with a different formulation for a fundamental diagram in 1953. His model accepts a variety of traffic behaviors with and without congestion [46]. However, other negative characteristics of the original model were retained. The last, and probably the most accurate model from Van Aerde that seeks to address the previous problems was created in 1995 [46]. In this model, the speed of the vehicle reacts to the current density. This is beneficial for many road sections (tunnels, slip roads, etc.). However, as majority of these models, this model has been developed primarily for freeways.

Because traffic simulation is not generally intended for high speed road sections, some of the current traffic simulators have begun to solve problems with their quality through the so-called online simulation [6]. They use the principle of vehicle injection at particular points of the road network. If the results of the simulation in a given road section differ from the real state, they either simply „subtract“ the vehicle at the given location, or, conversely, dynamically „add“ it. In this case, the simulation model does not need to be very precise. On the other hand, the actual injections, the number of which can be relatively high, significantly restrict the use of the simulator.

2.1.5 Scalability and Speed of Simulation Models

One of the problems of microscopic traffic simulators is their performance. None of them has primarily been designed for long-term forecasting. Hence, the models are not suitable for integration to ITS for traffic state predictions [10, 5]. Some of them were accelerated in order to achieve higher performance and to deploy them in larger areas and to enable multiple real time execution. However, as the authors claimed, the obtained results have never achieved a sufficient quality [22].

The acceleration was enabled by specialized equipment [55] or parallelization by means of threads which can be effectively mapped into a multicore processor (e.g. [27]). However, the concept is not primarily designed for accelerating the simulation. The primary goal was to expand capabilities for simulating larger areas. The so-called modular approach is another main direction in the acceleration of traffic microsimulation programs. In this case, the entire simulation network is divided into several sub-networks which are simulated independently [13].

The presented techniques can be employed to accelerate other types of simulation models [10, 5]. The possibility of the parallel microsimulation in such a way that the used parallelization technique can be implemented on a multicore system, should be an inherent feature of modern microsimulation models [12]. It means that a good traffic simulation model has to be constructed with the aim of parallel processing instead of making some effort to accelerate an inappropriate model. The acceleration of microsimulation model is seen as a quite complicated task and extra effort has to be invested to it. As a result, some new methodologies and strategies are gradually emerging [42].

2.2 Cellular Automata in Traffic Microsimulation

Cellular automaton (CA) is a computational model inspired in biology and developed to model massively parallel, locally interacting and self-replicating systems [49]. As defined, for example in [50], it is a d-dimensional grid of finite automata (known as cells) that operate according to their *local transition functions.* The cells work either synchronously, where each state of every cell is calculated from its previous state and the previous states of cell's neighbors synchronously with a synchronization signal, or asynchronously, where the cells can change their state independently of each other (e.g. [54]). By a configuration of the cellular automaton we mean the state of all the cells at a given moment. The global behavior is captured in the *global transition function*, which defines a transformation from one configuration to the next configuration of the cellular automaton. If all cells operate according the same local transition function (rule), the automaton is called *uniform.* Otherwise, it is called *non-uniform.* This type of CAs was introduced, because it can show a more complicated behavior than uniform ones. The rules can be deterministic or probabilistic. In general, the CA model supposes that the number of cells is infinite. However, in the case of practical applications, the number of cells is finite. Then it is also necessary to define the *boundary conditions*, i.e. the setting of the boundary cells.

Cellular automata have been applied in many scientific areas, especially for the modeling of complex (biological, chemical, computational, etc.) phenomena. They enable the modeling of discrete dynamic systems, in particular those in which the interaction of a given element is limited to its local surrounding. The global behavior is caused locally by many interacting elements. It can be observed that microscopic traffic models share many properties with CA.

The first microsimulation traffic model based on CA was introduced in 1992 and used to simulate a one-directional cyclically bounded section of the road [40]. In this traffic simulation model, each cell represents a certain part of the road section at a constant length (7.5 meters). The local transition function of the cell defines a new state based on the current status and availability of several neighboring cells. Each cell maintains the information about presence of a vehicle. If a vehicle is present, its parameters (e.g. vehicle speed in the original model [40]) are given. The distance, which the given cell (i.e. driver in the vehicle) can monitor, is defined by the number of neighboring cells. A CA cell may also define the type and, for example, the limitations of the road section, which it represents. The local transition function can be formulated, provided that each vehicle in the cell has a certain speed in the defined range and it is possible to determine the free space (the number of free cells), in front of (and in the event of overtaking also behind) the occupied cell.

Reflecting the criticisms, the CA based traffic simulation models have been modified in many different ways [32, 48, 16, 58, 57]. As the model parameters can be tuned it is possible to change properties of the model. It was shown that CA-based models can show a non-trivial and realistic behavior, while also being capable of reproducing all the phenomena that occur in traffic [40, 32, 48, 16]. Because of their simplicity, they are capable of performing several million updates per second even on an ordinary computer. This means, among other things, that they can be used to simulate very large traffic networks or they can be used for simulation of the areas with a very high traffic density (the number of simulated entities). They are, therefore, very useful in the area of the traffic microsimulations. Their simplicity predisposes them to parallel implementations on multicore computers or, for example, for implementations directly in specific integrated circuits [55]

2.3 Evolutionary Algorithms for Model Calibration

Evolutionary algorithms (EAs) are stochastic optimization algorithms inspired by biological evolution observed in nature [9]. The main branches are genetic algorithms, genetic programming, evolution strategies and evolutionary programming.

Candidate solutions, also called *individuals*, are usually coded as strings of symbols – the so-called *chromosomes.* At the starting point, a collection of individuals *(population)* is generated randomly. In order to evaluate the solutions encoded in the population, a mapping (or decoding) process is usually performed firstly. This transforms every chromosome to a candidate solution – the so-called *phenotype* which can be then evaluated.

The *fitness function* gives a measure of how good a given solution is for the target task. If the fitness of candidate solution is measured with regard to multiple objectives, the algorithm is called the *multi-objective optimization.*

There are several ways how to select individuals for creating a new population. A common way is to use fitness-proportionate selection, where an individual is given a probability of being drawn for reproduction proportional to its fitness score. An alternative to this is *tournament selection* where a number of individuals are drawn randomly and the individual with the highest fitness score of this selection is chosen for reproduction. The selected individuals are subject of various operations before they are inserted into the population of individuals constituting the new generation. The most common form of the variation operators used is called *mutation.* By applying this operator, a small change in the chromosome is performed. Recombination is done using the *crossover* operator, which swaps and exchanges some parts of two parent chromosomes. A common way of speeding up the whole process of evolution is to include *elitism.* This performs transferring the fittest individual of a given generation to the next one. However, this usually depends on the context and there may be situations where the elitism is not advantageous. A new population is established from newly generated individuals and some members of the previous population.

Genetic algorithm (GA) is one of the most popular variants of EAs [23]. In the case of GAs, the chromosome consists of a string of consecutive genes, often bits, which can be mapped into a phenotype. In this case, the mutation means inverting one or few bits. On the other side, it is also possible to operate on integers, floating point numbers and other entities by means of more advanced mutation operators. The crossover operator has several variants of exchanging parts of chromosomes.

In the context of this work, GA has been utilized in two scenarios connected with the traffic simulators. The first one is in the sensitivity analysis for the proper selection of optimized parameters [35, 34, 51]. Here, GA replaces standard techniques of probabilistic sensitivity analysis (e.g. *Monte Carlo*) with quite good results. With the proper optimization parameters chosen, the whole simulation model can be optimized and thus deployed significantly faster (compared to the „manual tuning process") [24].

Other usage of GA is for optimization of all model parameters (or at least those ones chosen on the basis of the sensitivity analysis). However, the authors commonly use only speed-flow-density relations in the traffic fundamental diagram instead of the real microscopic data. For example, in [31], the authors proposed a generic traffic microsimulation parameter optimization tool that uses genetic algorithms. Their framework was included into *PARAMICS* traffic simulation tool and utilized in Port Area network in downtown Toronto, Canada for estimating speed-flow relations. Another example of calibration of microscopic traffic simulation models using GA has been presented in [53]. The authors estimate the origin-destination (O-D) flows jointly with the behavioral parameters in *MITSIMLab* model. Even in more recent research (2016), the microsimulation models are still calibrated to macroscopic data (e.g. *AIMSUM* [14]). Moreover, all mentioned research is focused especially on one type of facilities – the freeways.

2.4 Challenges Addressed in the Thesis

The research presented in the thesis extends the previous research in several ways. Instead of the macroscopic data we also employ the microscopic data in order to perform the calibration. Microscopic data (e.g. travel times) can be compared one-to-one (e.g. vehicle-by-vehicle or driver-by-driver) and thus the results can easily be compared to other calibrated simulators. The simulation results based on the macroscopic data have been previously compared by means of their plots in time. For those situations where the macroscopic data are still desired (e.g. due to planning purposes where the behavior of elementary entities is not so important), we propose a methodology for a precise mathematical comparison of given results. Furthermore, the thesis primarily deals with the simulation of different facilities, i.e. not only freeways.

Chapter 3

Research Summary

This chapter summarises the research conducted in the thesis. First, a brief overview of the research process is given. Then motivation and abstracts for each included paper are presented. Finally, the all other relevant publications produced during the research are listed.

3.1 Overview

The research presented in the thesis started with a detailed analysis of all traffic phenomena that must be reproduced in any realistic traffic simulation model. Then a suitable CA-based microsimulation model has been chosen and analysed in a greater detail in Paper I. Next, our focus was shifted to the model acceleration to support the multiple in real time simulations. Some explorations were undertaken in Paper I and a more scalable solution was presented in Paper II. As a suitable scalable solution has been found, the work was then directed to model validation and calibration. The first results were published in Paper III for the macroscopic data and an evolutionary calibration has been utilized for the first time. At this stage, the focus was also shifted towards evaluation of the competitiveness of the proposed system. Paper IV included a basic comparison with the current state-of-the-art systems. In Paper V, improved calibration process was introduced including the data used to address real sensors behavior.

3.2 Papers

This section presents relevant details, motivation and contributions for each paper together with the paper abstract.

3.2.1 Paper I

A Scalable Cellular Automata Based Microscopic Traffic Simulation

As the traffic modeling for the real-world applications was one of the main goals of the research, a deep analysis of all traffic phenomena was desirable. Such analysis is covered within this paper. Moreover, this paper focuses on selection of an appropriate model that should be used in the next research. As none of existing models has been perfectly suitable for precise and very fast simulations, a new model (based on the cellular automaton) has been developed. The corresponding simulator has been validated and tested with the

standard symmetric multiprocessor (SMP) architecture.
This work resulted in the basic implementation of the simulator based on the brand new microsimulation model that is suitable for an acceleration by means of common parallel architectures.

Abstract

This paper presents a new model for simulations of very large scale traffic networks. The proposed model is based on microscopic cellular automata (CA) extended to eliminate unwanted properties of ordinary CA based models, such as stopping from maximum speed to zero in one time step. The accuracy of the model has been validated by comparisons with various fundamental diagrams. A parallel implementation developed using the proposed model allows for an almost linear speedup. This allows to run a simulation multiple in real-time, that the traffic state of very large scale networks can be precisely predicted, for example, with various scenarios.

3.2.2 Paper II

Cellular Automata Based Traffic Simulation Accelerated on GPU

The main motivation for the research covered in this paper is in the need for even faster multiple in real time simulations for the real ITS deployment. A faster simulation will enable us to perform and evaluate more different strategies and scenarios. As modern graphic processing units (GPUs) began to contain more and more powerful (SMP) processing cores, the paper was focused on their utilization in our simulator.
This work resulted in a scalable and effective solution for previously proposed simulator which can now be accelerated on GPUs. Also some architecture depending limitations have been investigated.

Abstract

Intelligent transportation systems become more and more important with the increasing traffic densities and safety requirements. A reasonably good traffic prediction can be obtained using microscopic traffic simulation models witch distinguish and trace every traffic entity. However, microscopic simulation requires considerable computing resources. In this paper, we propose to accelerate a cellular automata based microscopic traffic simulator using graphic processing units (GPU). The proposed accelerator provides speed-up of 204.65 with respect to a single core solution for problems instances containing 170 mil. cells, equivalent to 935 000 km of traffic network. This solution is sufficient to predict traffic simulations multiple in real-time.

3.2.3 Paper III

Evolutionary Approach to Calibration of Cellular Automaton Based Traffic Simulation Model

The proposed scalable solution presented in the previous papers has to be calibrated and validated before the real usage. However, due to missing real data in our early research, suitable mathematical models such as Van Aerde model (operating with the macroscopic data) are utilized for the calibration. For the first time, we have utilized a evolutionary

algorithm in the calibration process in the way that traffic expert is not forced to set any of the model parameters.
This work resulted in a brand new methodology for the comparison of simulation results based on macroscopic variables. A new approach for the calibration of the model has been proposed.

Abstract

Microscopic traffic simulation models have become very popular in the evaluation of transportation engineering and planning practices in the past few decades. To achieve high fidelity and credibility of simulations, a model calibration and validation must be performed prior to deployment of the simulator. In this paper, we proposed an effective calibration method of the microscopic traffic simulation model. The model is based on the cellular automaton, which allows fast large-scale real-time simulation. For its calibration, we utilized a genetic algorithm which is able to optimize different parameters much better that a human expert. Furthermore, it is possible to readjust the model to given field data coming from standard surveillance technologies such as loop detectors in our case. We have shown that the precision of simulations can be increased by 20 % with respect to a manually tuned model.

3.2.4 Paper IV

Calibration of Traffic Simulation Models Using Vehicle Travel Times

In our previous work we have used the data on the macroscopic level of detail. As some types of truly microscopic data are becoming more available and we are able to get the microscopic data from our partners, we could use them in our research. The whole calibration process was updated in order to exploit these microscopic data.
As a result of this work, we were able to use our calibration process to find out a very competitive solution that is stable for different microscopic data sets. Moreover, it was shown that our automated process of calibration is able to find parameter values that are hard to determine or even estimate with the other common techniques.

Abstract

In this paper, we propose an effective calibration method of the cellular automaton based microscopic traffic simulation model. We have shown that by utilizing a genetic algorithm it is possible to optimize various model parameters much better than a human expert. Quality of the new model has been shown in task of travel time estimation. We increased precision by more than 25 Moreover, we were able to calibrate some model parameters such as driver sensitivity that are extremely difficult to calibrate as relevant data can not be measured using standard monitoring technologies.

3.2.5 Paper V

Advanced Approach to Calibration of Traffic Microsimulation Using Travel Times

The motivation for the final paper was to deal with real properties of traffic sensors, e.g. when some data are often missing in data sets. Moreover, we begin to use the raw data

from the sensors instead of their statistical properties.
This research and deployment resulted in a complete system for calibration of microscopic traffic simulators based on cellular automata which is not only scalable and precise, but also competitive with other similar systems. Moreover, the proposed system can cope with incomplete data sets, and thus it can be adapted to the real world situations.

Abstract

An effective calibration method of the cellular automaton based traffic microsimulation model is proposed in this paper. It is shown that by utilizing a genetic algorithm it is possible to calibrate different parameters of the model much better than a traffic expert. Moreover, using this process it is also possible to find several model parameters that are extremely difficult to calibrate as relevant data can not be measured using standard monitoring technologies or complete data sets are often not available. The quality of the new calibrated models is discussed in the task of vehicle travel time estimation. The precision of simulations is increased over three times compared to a manually tuned model. The average error rate is 10.75.

3.3 List of Publications

Papers Included in Thesis

I KORČEK Pavol, SEKANINA Lukáš and FUČÍK Otto. A Scalable Cellular Automata Based Microscopic Traffic Simulation. In *Proceedings of the IEEE Intelligent Vehicles Symposium 2011 (IV11).* Baden-Baden: IEEE Intelligent Transportation Systems Society, 2011, pp. 13-18. ISBN 978-1-4577-0889-3. [70 %]

II KORČEK Pavol, SEKANINA Lukáš and FUČÍK Otto. Cellular Automata Based Traffic Simulation Accelerated on GPU. In *Proceedings of the 17th International Conference on Soft Computing (MENDEL2011).* Brno: Institute of Automation and Computer Science FME BUT, 2011, pp. 395-402. ISBN 978-80-214-4302-0. [70 %]

III KORČEK Pavol, SEKANINA Lukáš and FUČÍK Otto. Evolutionary Approach to Calibration of Cellular Automaton Based Traffic Simulation Model. In *Proceedings of the 15th International IEEE Conference on Intelligent Transportation Systems (ITSC2012).* Anchorage: IEEE Intelligent Transportation Systems Society, 2012, pp. 122-129. ISBN 978-1-4673-3062-6. [70 %]

IV KORČEK Pavol, SEKANINA Lukáš and FUČÍK Otto. Calibrating Traffic Simulation Model Using Vehicle Travel Times. In *Proceedings of the 10th International Conference on Cellular Automata for Research and Industry (ACRI 2012).* Berlin: Springer-Verlag, 2012, vol. 7495, pp. 807-816. ISBN 978-3-642-33350-7. [70 %]

V KORČEK Pavol, SEKANINA Lukáš and FUČÍK Otto. Advanced Approach to Calibration of Traffic Microsimulation Models Using Travel Times. In *Journal of Cellular Automata (JCA).* Philadelphia: Old City Publishing, Inc., 2013, vol. 8, no. 6, pp. 457-467. ISSN 557-5969. [70 %]

Other Relevant Papers

- KORČEK Pavol, SEKANINA Lukáš a FUČÍK Otto. Towards Scalable and Accurate Microscopic Traffic Simulation Using Advanced Cellular Automata Based Models. In: *Proceedings of the 13th International IEEE Conference on Intelligent Transportation Systems Workshops.* Madeira Island: IEEE Intelligent Transportation Systems Society, 2010, s. 27-35. ISBN 978-972-8822-20-0. [70 %]
- KORČEK Pavol, SEKANINA Lukáš a FUČÍK Otto. Microscopic Traffic Simulation Using CUDA. In *Advanced Computer Architecture and Compilation for High-Performace and Embedded Systems (ACACES 2011) Poster Abstracts.* Fiuggi: Academia Press, 2011, s. 207-210. ISBN 978-90-382-1798-7. [70 %]
- PETRLÍK Jiří, KORČEK Pavol, FUČÍK Otto, BESZÉDEŠ Marián a SEKANINA Lukáš. Estimation of Missing Values in Traffic Density Maps. In *Proceedings of the 15th International IEEE Conference on Intelligent Transportation Systems (ITSC2012).* Anchorage: IEEE Intelligent Transportation Systems Society, 2012, s. 632-637. ISBN 978-1-4673-3062-6. [15 %]

Chapter 4

Discussion and Conclusions

This chapter discusses the approach followed in the thesis. In addition, the achieved results are summarised and discussed. Finally, conclusions and possible directions for future work are presented.

4.1 The Approach

An analysis of recent scientific and commercial traffic simulation tools and a study of the current acceleration, calibration and validation techniques have been performed within this research. Some of the studied tools are reported in the introduction to the thesis. In order to validate an optimize the proposed methods, various contacts were accordingly established with research and public institutions which enabled to acquire real data from traffic sensors at both macroscopic and microscopic level of detail. The data were obtained from universities (University of Žilina – The Faculty of Operation and Economics of Transport and Communications, Czech Technical University in Prague - The Faculty of Transportation Sciences and University of Pardubice - The Jan Perner Transport Faculty) and commercial companies operating in the transport sector (Camea, spol. s r.o., Road and Motorway Directorate of the Czech Republic and Technical management of roads in Prague), but also from several publicly available international sources such as the Research Data Exchange (RDE) database maintained by the U.S. Department of Transportation, Federal Highway Administration[1]. All concrete research steps are presented in description of published scientific papers mentioned earlier in the thesis (see Chapter 3).

4.2 Software Outcomes

During the research, several software tools were developed and actively used. When calibrating a simulator, process can fail when not all proper data are available, for example, when a road segment is not covered by sensors. In order to calibrate for macroscopic data (e.g. traffic flow), software *TRAffic SEnsor LOcation* (TRASELO)[2] capable of tracking such missing data was developed. On the basis of a given traffic network topology (where the nodes represent intersections and the edges are roads, see Fig. 4.1), with several traffic sensors embedded, this program calculates and generates the remaining values. Moreover, *TRASELO* suggests the sites where new sensors should be installed in order to enable the

[1] Available at: www.its-rde.net

[2] Available at: www.fit.vutbr.cz/research/view_product.php.en?id=297

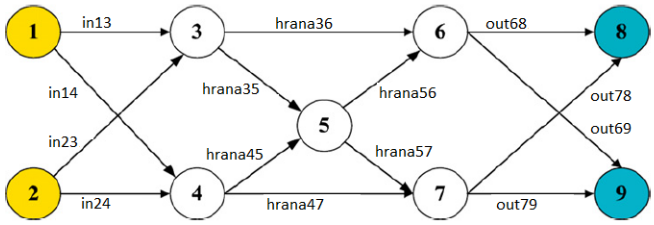

Figure 4.1: TRASELO network example.

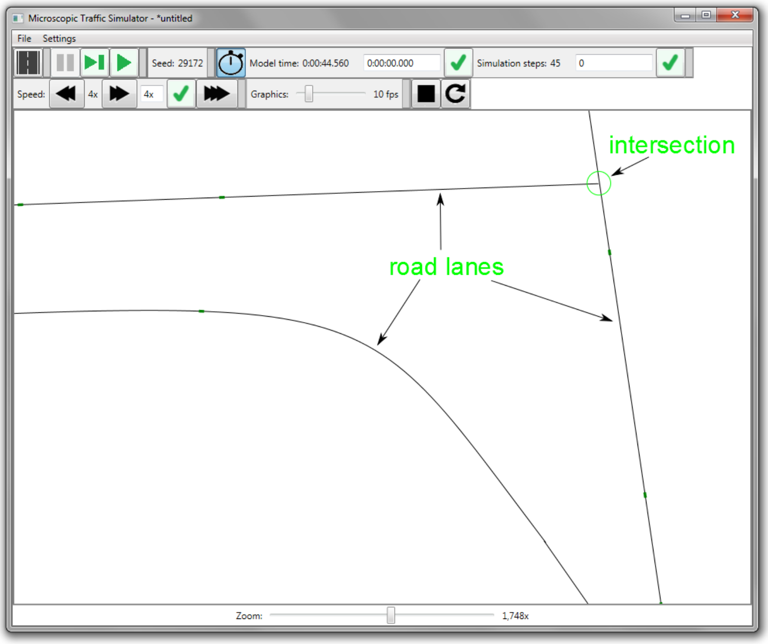

Figure 4.2: Simulation of a given topology in the microsimulation.

calculation of the remaining and greatest possible number of missing values. The method used in this program is based on the linear algebra (matrix operations) and it is inspired by paper [41].

In addition, a simple road traffic microsimulator[3] with a graphical user interface was developed. It is based on the principle of cellular automaton, as presented in this work, and intended for an experimental evaluation of certain traffic phenomena produced with the aid of simulation. Its user interface (see Figure 4.2) enables the road topology to be constructed with several lanes and intersections. This software supports modeling of the unmarked intersections, major-minor road intersections and intersections with traffic lights, and can even be used for roundabouts. The macroscopic data are generated and graphically displayed during the simulation, while the microscopic data can be exported and imported using the most recent version of the tool. Changing the local transition function and possibly other parameters (see Figure 4.3) allows the model to be adapted to the results of the calibration process.

[3] Available at: http://www.fit.vutbr.cz/research/view_product.php.en?id=314

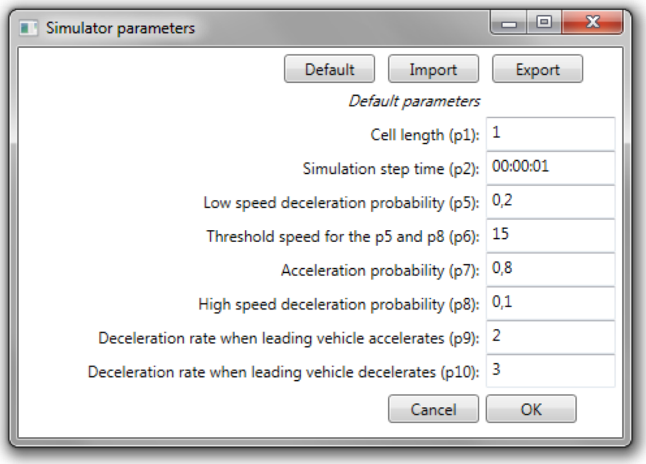

Figure 4.3: Setting the parameters of the microsimulation.

4.2.1 Scalability

The problem of scalability seen in the microsimulators involves not just the modeled topology dimensions, but also the number of simulated entities (vehicles, etc.). The demand for computing performance is growing as the traffic density increases. For a fair comparison of our model under different conditions, *TRANSIMS*[4] microsimulator was selected. *TRANSIMS* is more powerful than the commercially used *VISSIM*[5] in a simple parallelization by means of the job distribution among 16 computers [39], something which today can be replaced with a single multicore processor. Due to this, as well as due to its unavailability (without a graphical extension), the *VISSIM* was not chosen for the comparison. Instead, *MATSIM*[6] - a multi-agent traffic simulation tool was selected, with its latest performance modifications [56]. Finally, a command-line version of *SUMO*[7] microsimulation tool was also incorporated into our comparison. The choice was made with respect to the availability and practical use of these tools. Moreover, an assessment by the scientific community was taken into account as well [19].

The whole simulation took place in a synthetic testing environment created with mentioned tools under the same traffic conditions. Namely, a 30-kilometer-long road network and a random generation of incoming vehicles with the same vehicle arrival probability distribution at different filling densities were considered. An average runtime out of ten runs for one-hour modeled traffic situation with 10% traffic density was taken as the reference. The runtime for every selected microsimulator was also calculated in the same manner for other densities (20%, 30% and 40%). Table 4.1 shows the time multiple necessary to simulate the same segment compared to the reference time (with 10% traffic density). The simulations were carried out on a machine with two processors Intel® Xeon® E5-2650 v3 (25M Cache, 2.30 GHz, 10 cores and 20 threads per processor) with 32 GB of RAM in total. There was no specialized acceleration routine implemented and the models used were not calibrated, except using the same initial settings (the vehicle/driver type and parameters).

[4] Available at: https://sourceforge.net/projects/transims/
[5] Available at: http://vision-traffic.ptvgroup.com/en-uk/home/
[6] Available at: http://www.matsim.org/
[7] Available at: http://sumo.dlr.de/wiki/Main_Page

	Our model	**TRANSIMS**	**MATSIM**	**SUMO**
10 % density	*1.00*	*1.00*	*1.00*	*1.00*
20 % density	*2.02*	*2.01*	*3.74*	*3.32*
30 % density	*3.00*	*3.02*	*4.58*	*6.98*
40 % density	*4.01*	*4.00*	*5.31*	*12.33*

Table 4.1: Scalability comparison of selected tools: the time multiple necessary to simulate the same segment compared to the reference time (with 10% traffic density).

Manually tuned	**Set 1**	**Set 2**	**Set 3**
23.44	*13.96*	*17.80*	*14.80*

Table 4.2: An average error in % on macroscopic datasets (from the paper included in Chapter 3.2.3).

As can be seen from Table 4.1, the simulator based on our model is very similar in terms of performance to *TRANSIMS*. For higher densities, both tools require a proportional increase in the simulation time necessary to finish, which was not the case in the remaining simulators. The reason is that both simulators are based on the same principle of a well-scalable cellular automaton. However, the *TRANSIMS* publicly available sources indicate that it has not been modified or tested to run effectively on other acceleration platforms such as graphics cards (GPGPU). This was also confirmed in an opinion provided by an author whose paper in 2013 [52] referenced our paper discussed in Chapter 3.2.1. The author points out that the GPGPU parallelization approach seems to be extremely suitable because GPGPUs are constantly elevating their power. It should also be noted that both tools are capable of performing the simulations several times faster than in real time, which is not true for the other chosen microsimulation tools.

4.2.2 Accuracy and Robustness

In the papers included into the thesis, the quality of our model and the simulator based thereon was compared on different data sets. Results on test data sets, both macroscopic and microscopic, have been already published. For a basic comparison, the accuracy of the initial and manually tuned models has always been presented. These results are briefly summarized in Table 4.2, Table 4.3 and Table 4.4.

A comparison with the other existing models and microsimulation tools is not straightforward because every author shows the quality on its own data. Such data are not often publicly available due to the exclusive ownership of the providers. If the relevant model was available then it would be possible to compare these models with either our data or publicly available data as described earlier.

Manually tuned	**Set 1**	**Set 2**
32.3	*19.23*	*15.21*

Table 4.3: An average error in % on macroscopic datasets derived from the microscopic data (from the paper included in Chapter 3.2.4).

Manually tuned	Set 1	Set 2	Set 3	Set 4
34.31	*11.19*	*9.89*	*11.27*	*10.64*

Table 4.4: An average error in % on pure microscopic data sets (from the paper included in Chapter 3.2.5).

	Set 1	Set 2	Set 3	Set 4
Our model	*11.19*	*9.89*	*11.27*	*10.64*
TRANSIMS	*15.13*	*12.19*	*18.45*	*21.25*
MATSIM	*85.25*	*89.31*	*91.18*	*89.67*
SUMO	*19.88*	*13.76*	*21.39*	*23.52*

Table 4.5: An average error in % on pure microscopic data sets (according to the paper included in Chapter 3.2.5).

For such a comparison, the tools mentioned in Chapter 4.2.1 were chosen and calibrated according to the procedures set out specifically for each tool [44, 8]. Only the *MATSIM* tool was used „as-is“ because there was no calibration method appropriate for the selected data, namely the microscopic data prepared in our previous research. In this data, some values are also missing as described in the paper included in Chapter 3.2.5. The results are summarized in Table 4.5.

It is evident that our calibration procedure is able to calibrate the proposed microsimulation model significantly better than other tools. The method scores better in terms of several percent points on used data. Our calibrated model has also been employed as a reference model for other authors [59].

An evolutionary calibration method for traffic microsimulators appears to be robust in several aspects. First, there is no need for a sensitivity analysis, which is quite complicated in models with many parameters, as has been demonstrated in [15]. It is due to the basic principle of the evolutionary approach which chooses the parameter values by its own. And even for different traffic facilities it is able to optimize different model parameters. This is also confirmed in a recent study published in 2015 [37] and related work, which among other things analyzed the possibility of employing several calibration techniques for the purpose of calibration of traffic simulators. The authors included our work for the reference. Furthermore, the method is robust regarding the missing data (see data set 3 and 4 in Table 4.5) because in such a case an appropriate setting of the microsimulation model parameters capable of precise simulations can be found. In this case, the other simulators are not precise enough.

4.3 Conclusions

The main contributions of the thesis can be summarized as follows:

- Development of a brand new traffic microsimulation model that is scalable and thus applicable for a) large-scale areas, b) high density areas and c) high-speed multiple in real time scenarios.

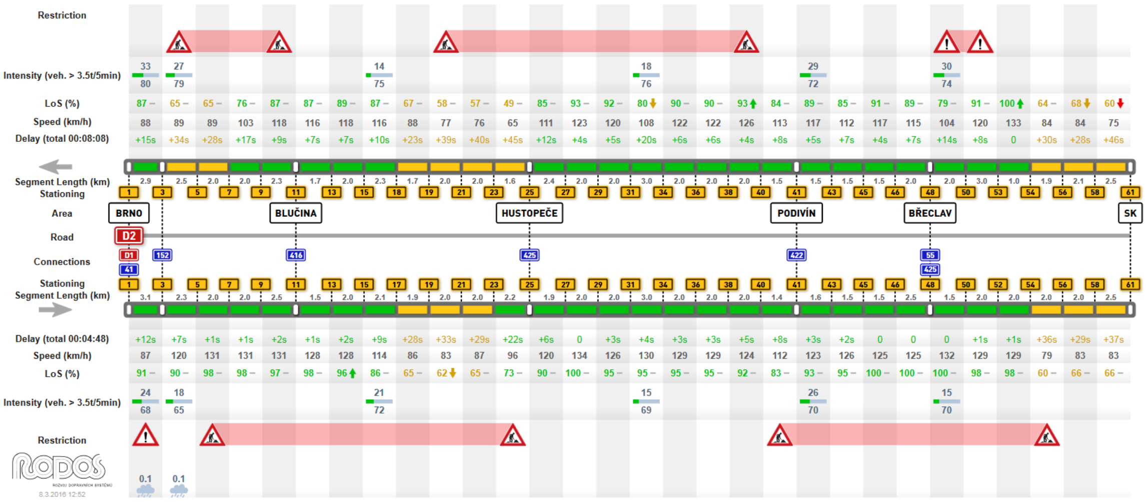

Figure 4.4: RODOS online system preview. Source: http://rodos.vsb.cz.

- Design of a brand new calibration procedure that allows to perform highly precise simulations a) without the need for sensitivity analysis, b) capable of utilizing both micro- and macroscopic data and c) capable of adopting to real-world sensors conditions.

It can be concluded that the thesis has contributed to the initial goal of developing a fast, scalable and accurate or highly precise traffic simulator, capable of multi-real-time simulations of complex traffic areas.

4.4 Future Work

Traffic engineers and other specialists are continuously improving ITS. There is a growing interest in deployment of the microsimulation tools in the traffic states forecasting as stated at the beginning of the thesis. It also happens in the Czech Republic and, therefore, the *RODOS* centre has been established in 2012. It is currently the biggest active subject in the field of applied transport research with the main focus on road transport monitoring and control as well as its funding. It consists of three biggest technical universities, one public research institution and six commercial companies that rank among leading players in the fields of IT, software, data collection and practical implementation of ITS on the Czech market. The strategic objective of the Centre is to create a complex information „superstructure“ for road transport by means of new transport informatics tools and to integrate it into existing ITS.

RODOS is developing *Dynamic Mobility Model of the Czech Republic* (DMM). It integrates dynamic models of passenger, vehicle and goods mobility and related information in the entire area of the Czech Republic. The model and its operation will be utilised extensively not just in transport and other network industries but also in processes of the state and public administration [43].

RODOS DMM uses databases and several predictive features build upon them. These databases consist of several data streams coming from various sensors and so the traffic data needed for the proper microsimulation are also present. The scalable microsimulation model with a highly precise calibration method created in this work will be integrated to this system. It can be deployed to allow performing precise short and long term traffic states forecasting when calibrated for various facilities. It will be a big opportunity to try our model in simulating unexpected traffic events (such as accidents and other types of collisions). This will need further experiments with the whole system and it will be definitely interesting and challenging continuation of the work started in the thesis.

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