TRANSPORT AND TELECOMMUNICATION INSTITUTE

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# DEVELOPMENT OF NEW APPROACH FOR SIMULATION AND ANALYSIS OF TRAFFIC FLOWS ON MESOSCOPIC LEVEL

**Summary of the promotion work**

to obtain the scientific degree of Doctor of Science in Engineering (Dr.sc.ing.)

Scientific area "Transport"
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**Scientific supervisor**
**Dr. habil. sc. ing., professor**
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**THE PROMOTION WORK PRESENTED TO THE TRANSPORT AND TELECOMMUNICATION INSTITUTE TO OBTAIN THE SCIENTIFIC DEGREE OF DOCTOR OF SCIENCE IN ENGINEERING (Dr.sc.ing.)**

**OFFICIAL REVIEWERS:**

The defence of the thesis will be held at o'clock at the special Promotion Council of Transport and Telecommunication Institute on award of a doctor's degree, at 1, Lomonosova Street, Conference Hall 130, Riga, Latvia, tel. +371 67100594, fax: +371 67100535.

CONFIRMATION

I hereby confirm that I have developed the promotion work presented to the Promotion Council of Transport and Telecommunication Institute to obtain the scientific degree of Doctor of Science in Engineering. The promotion work has not ever been presented to any other promotional council to obtain the scientific degree.

.............................Mihails Savrasovs

The promotion work is written in English, it contains an introduction, 5 chapters, conclusions, 59 figures, 26 tables, 134 pages, and 7 appendixes. Bibliography contains 103 sources.

## GENERAL DESCRIPTION OF THE THESIS

### Introduction

Since 1886 when the first engine of a vehicle was patented the number of vehicles on roads was growing dramatically. This led transport planners and researchers to search new methods of development and optimisation of transport infrastructure. Finally, the concepts of a sustainable transport system were formulated as a strategic and complex decision, which should be applied. The development of a sustainable transport network is a complex problem, which should embrace all aspects of transport systems - from permanent survey of traffic volumes and households to the development of new technologies in such areas as petroleum production and vehicle engine modernization. Among different kinds of tools used for the development of a new generation of transport systems, a specific place is held by optimisation of the existing transport infrastructure and a strict and extended analysis of the impact of new infrastructure elements on another parts of transport infrastructure. Usually this point leads to the use of different tools of traffic flow analysis. Among the existing tools for traffic analysis, simulation is one of the most powerful tools for solving tasks originating in process of real system design and renovation.

### Research motivation

Simulation is a powerful tool for traffic system analysis. The existing microscopic and macroscopic simulation models have a number of disadvantages. The existing disadvantages of microscopic and macroscopic simulation motivate the development and research of a new type of models, called mesoscopic. Mesoscopic models should avoid disadvantages inherent in microscopic and macroscopic models. But the obscurity of the concept of mesoscopic simulation urges many scientists and researchers to develop a number of different mesoscopic models. Most of the existing mesoscopic models are developed theoretically, without any implementation in the form of software, or are realized in software which is not available for researchers and practitioners. These facts motivate the development of a new mesoscopic approach for traffic flow simulation, which will be available for potential users (researchers and transport planners).

**The goal and the tasks of the promotion work**

The goal of the promotion work is as follows: Development, investigation and application of a new type of model in the class of mesoscopic traffic models. As regards the above-mentioned goal of this research, the following tasks are posed:

1. To consider problems of traffic system simulation modelling.
2. To conduct the analysis of
   a) the currently used traffic systems simulation tools
   b) the existing simulation approaches and detailed mesoscopic traffic models.
3. To offer and develop the concept of the new type of traffic mesoscopic model.
4. To develop the models with synthetic and real data, providing for numerical examples of the offered mesoscopic approach.
5. To test the validity of the new type of traffic mesoscopic model by different examples.
6. To demonstrate the advantages and disadvantages of the offered model.
7. To provide scientifically-grounded recommendations on model use.

**The object and subject of research**

The object of research is traffic flow. The subject of research is simulation-based models of the traffic flow.

**Degree of the theme study**

The history of the traffic flow simulation began in 1955 by D.L.Gerlough's issuing his thesis: "Simulation of freeway traffic on a general-purpose discrete variable computer" at the University of California, Los Angeles. From that time on, a number of scientists and practitioners made efforts toward the development of traffic simulation theory. The following could be mentioned with regard to the microscopic simulation of traffic flows: R.Wiedemann in 1974 has published a description of 74 Wiedemann car-following models in his article "Simulation des Straßenverkehrsflusses", P.G.Gipps in 1970 developed a Gipps' car-following model; some other works by R.E.Chandler, D.C. Gazis, G.Lee, J.C.Bender, R.E.Fenton etc. could me mentioned as well. The research of these scientists helped to create a basis for traffic flow simulation software. In the meantime, a development of macroscopic models was started. Macroscopic traffic models take into consideration cumulative traffic stream characteristics (speed, flow, and density) and the interrelationships between them. Here, a number of scientists could be mentioned referring to the macroscopic simulation: M.J.Lighthill, G.B.Whitham, P.I.Richards, C.F.Daganzo, S.K.Godunov etc.

The disadvantages of these simulation approaches motivate one to develop another class of traffic simulation models which are called mesoscopic. In 1989, D.R. Leonard proposed a model called CONTRAM. The model assumes grouping of vehicles into pockets and routing them through the network. Another scientist, M. Ben-Akiva, proposed a mesoscopic model DYNAMIT in 1996. This model grouped vehicles by cells, which define such properties like speed etc. A bit earlier in 1994, R. Jayakrishnan proposed a queue-server approach application for traffic flow simulation. This idea became popular, and the model FASTLANE was presented by C.Gawron in 1998 and, subsequently, the model DTASQ – by M. Mahut (in 2001). Application of cellular automata for traffic flow simulation was made by B.W. Bush by development of TRANSIMS. The last widely known paper dedicated to mesoscopic model was published in 2004 as doctoral dissertation by Wilco Burghout in Royal Institute of Technology (Stockholm, Sweden).

The analysis of the above-mentioned sources enables one to draw the following conclusions on practical application of mesoscopic models, motivating the author to undertake a study in this area:

- mesoscopic traffic flow simulation is a very perspective type of simulation in terms of lack of any high requirements to input data and a low time of model development and experimentation, etc;
- the term “mesoscopic traffic model” still does not have any official definition (different scientists interpret it differently); this allows one to use different approaches to model development, but leads to confusion within scientific and transport planners’ community at the same time;
- mainly mesoscopic models are realized in proprietary software used by government institutions, or are developed without practical

approbation. This leads to scarcity of mesoscopic simulation tools on the market.

As a base for the development of a new type of mesoscopic traffic model, a Discrete Rate (DR) simulation approach is used. The concept proper of DR approach is based on event planning using piecewise linear aggregates, which were described by Buslenko in 1973. The DR approach was presented on Winter Simulation Conference by D.Krahl in 2009, who implemented this approach in ExtendSim software. In the meantime, prof. J.Tolujevs in his research demonstrated concepts and examples of DR application in logistics area.

**Research hypotheses**

The study puts forward the following hypotheses:

1. The Discrete Rate approach could be used for traffic flow simulation on mesoscopic level of detail.
2. The results obtained through application of the proposed model are adequate for further decision-making.

**The research methods**

The promotional work research is based on: system theory, methods of statistical data analysis, modern theory of simulation; analysis of scientific literature, scientific papers, press releases, EU Commission's reports, simulation guidelines, internal software manuals, and the Internet sources. The computer-based support for necessary investigations was: Microsoft Office Excel 2010, Statistica 8 package, PTV VISION VISSIM microscopic simulation software, and simulation software ExtendSim 8.

**The scientific novelty**

In the course of the work, the following results, which are new to the transportation engineering science, have been obtained:

1. The development of a new approach for traffic flow simulation based mainly on DR approach and called by author as DRTRM (discrete rate traffic reference model), which could be used by transport planners as a fast and exact tool in the course of decision support process.

2. The DRTRM methodology development for traffic simulation in research and practical applications.
3. The developed DRTRM methodology for traffic simulation can be used in scientific studies and practical work.
4. DRTRM validation results allowing one to accept the approach as credible.

**The practical value of research**

1. Development of methodology and algorithms for DRTRM usage in transport application.
2. Justification of the advantages of the proposed new mesoscopic traffic simulation model as against microscopic models, based on numerical examples.
3. Practical approbation of DRTRM use for specific Case Studies:
    a) The Project "Development of the Model of Intelligent Transport System of Europe-Asia Multimodal Corridor for Optimisation of Latvia-Belarus International Logistics Chain (TRANSLAB)" announced by Ministry of Education and Science of the Republic of Latvia (2007-2009).
    b) Latvian National Research Programme "Local Resouces Long-Term Utilization. New Products and Technologies (NatRes)". Project Nr. 4. „Development of the Long-Term Programme of the Latvian Transport System Harmonization" (LATRANS).
4. The obtained results became the basis for part of lectures delivered on the course: "Transport Modelling" of program 43525 "Transport Commercial Operations" and "Simulation modelling in transport and logistics" of program 4534507 "Transport and Logistics" of Transport and Telecommunication Institute.

**Scientific conferences and workshops**

The main results of the research are presented at 9 scientific conferences and workshops: 25th European Conference on Modelling and Simulation (Krakov, 2011); 1st International Conference on Road and Rail Infrastructure (Opatija, 2010); 23rd European Conference on Modelling and Simulation (Madrid, 2009); 2nd International Logistics PhD Students' Workshop (Magdeburg, 2009); International Conference ”Modelling of Business, Industrial and Transport Systems” (Riga, 2008); International Conferences ”Reliability and Statistics in Transportation and Communication” (Riga, 2012, 2010, 2008, 2007).

**Publications**

The results of the studies are published in 18 scientific editions. The list of author's publications could be found at the end of the abstract.

**Structure of the work**

The Promotional work consists of an introduction, 5 chapters, a conclusion, a list of references, and 7 appendices. The work comprises 134 pages and includes 60 figures and 23 tables. The list of references includes 103 sources. The structure of the work is as follows:

***Introduction***. The object and the subject of research are defined on the basis of actuality; a review of scientific literature has been carried out considering the issues related to the formulated goal and tasks of the research.

***Chapter 1. Review of traffic analysis tools.*** The types of traffic analysis tools are examined and classified, the role of simulation in transportation area is analysed, and trends in simulation-based traffic analysis tools are summarized.

The review and analysis of different models classified as mesoscopic, are presented. These are: CONTRAM, DYNAMIT, DYNASMART, FASTLANE, DTASQ, MEZZO, AMS and Cellular Automata.

***Chapter 2. Comparative analysis of simulation approaches.*** The place of DR approach among well-known classical simulation approaches as discrete event simulation, system dynamics, and agent-based simulation is emphasized. The comparison of these approaches is done on the general level and in detail.

***Chapter 3. Development of the concept of a mesoscopic discrete rate traffic simulation model.*** This chapter presents the DRTRM mesoscopic model for traffic simulation, treated as an extension of DR approach. Two alternatives of the model are formulated: the one for congested and the other for uncongested network. Mathematical formalisation of both is performed.

***Chapter 4. Comparing the developed approach with microsimulation. Case studies.*** This chapter demonstrates the use of DRTRM approach for simulation of a single, traffic light-controlled crossroad as well as simulation of two interconnected crossroads. Microsoft Excel and VBA are used to code both models. Simulation is based on synthetic data to show the idea of application of DRTRM approach for such a kind of simulation. Some results of simulation are presented as well; a kernel of the simulation model is shown in tabular form. The main idea of these examples is to show the simulation algorithm in details.

***Chapter 5. Mesoscopic simulation of an urban transport corridor.*** The last chapter demonstrates an example of simulation of the urban transport corridor using DRTRM approach. The urban transport corridor consists of 11 crossroads and most of them are controlled by traffic lights. The simulation is based on real input data obtained in the course of the traffic flow study project implemented in Riga city centre (2011). Within the framework of the project, the microscopic model was created, allowing one to test mesoscopic model output data against the already validated microscopic model. The mesoscopic model was created in ExtendSim simulation software. Special attention in this chapter is paid to determination of the form of the crossroad passing function used in proposed traffic model.

***Conclusions.*** Summary of the work, as well as main findings and conclusions are presented.

The list of author's publications, VBA code of models, different supporting tables and figures are to be found in ***Appendices.***

## SUMMARY OF WORK CHAPTERS

**Chapter 1** (Review of traffic analysis tools)

Traffic analysis tools is a collective term used to describe a variety of software-based analytical procedures and methodologies that support different aspects of traffic and transportation analyses. To date, numerous traffic analysis methodologies and tools have been developed by public agencies, research organizations, and consultants. Traffic analysis tools can be grouped into the following categories:

- **Sketch–planning tools.** Sketch-planning methodologies and tools produce general order-of-magnitude estimates of travel demand and traffic operations in response to transportations improvement.
- **Travel demand models.** Travel demand models have specific analytical capabilities, such as the forecast of travel demand and the consideration of destination choice, mode choice, time-of-day travel choice, and route choice, and the representation of traffic flow in the highway network.
- **Analytical/deterministic tools (HCM-based).** Most analytical/ deterministic tools implement the procedures of the Highway Capacity Manual (HCM). These tools quickly predict flow density, speed, delay, and queuing with respect to a variety of transportation facilities, and are validated with data fields, laboratory test beds, or small-scale experiments.
- **Traffic signal optimisation tools.** They are designed primarily to develop optimal signal-phasing and timing patterns for isolated, arterial streets, or signal networks. This may include capacity calculations; cycle length splitting optimisations, including left turns; and coordination/offset plans.
- **Macroscopic simulation models.** Macroscopic simulation models are based on the deterministic relationships of the flow, speed, and density of a traffic stream. The simulation in a macroscopic model takes place on a section-by-section basis rather than by tracking individual vehicles.
- **Microscopic simulation models.** Microscopic models simulate the movement of individual vehicles based on car-following and lane-changing theories. Typically, vehicles enter a transportation network using a statistical distribution of arrivals (a stochastic process) and are tracked through the network over small time intervals (e.g., 1 second or a fraction of a second).
- **Mesoscopic simulation models.** Mesoscopic simulation models combine the properties of both microscopic and macroscopic simulation models.

As this research deals mostly with simulation tools, only traffic analysis tools based on simulation will be taken into account hereinafter.

Traffic system models could be classified according to wide range of criteria. Some of them could be mentioned here:

- by solution: analytical vs simulation;
- by process representation: dynamic vs static;
- by variables scale: continuous vs discrete;
- by process: stochastic vs deterministic;
- by time changing approach: time-stepped vs event-based; etc.

But the most popular classification that is widely used is based on model detail level. Currently, 4 levels of the transport models are distinguished. They are as follows: sub-microscopic, microscopic, macroscopic, and mesoscopic models. Both microscopic and macroscopic ones are treated as classical and, generally, it's quite simple to define the meaning of these models. In the thesis, the author gives a detailed analysis of these models.

*Mesoscopic models.* The mesoscopic models are not so widely used. It is connected with the problem that scientists interpret the term "mesoscopic modelling" in different ways. Some researchers suggest that the mesoscopic modelling should integrate characteristics of both microscopic and macroscopic levels. They fall under the following definition: "Mesoscopic models combine the properties of both microscopic and macroscopic simulation models. These models simulate individual vehicles, but describe their activities and interactions based on the aggregate (macroscopic) relationships". Another definition sounds like "Mesoscopic models of traffic flows imply estimation of the macroscopic indicators on the microscopic level".

There is a number of simulation software products which are widely used. In the thesis the author presents a detailed analysis of these simulation tools. Some of them have become recommended tools for some countries, as for example, VISSIM/VISUM for Germany, AIMSUN for Spain, and PARAMICS for UK.

Simulation as a traffic analysis tool is now an everyday tool for practitioners and researchers in all fields of the profession.

In literature, the definition and concepts of mesoscopic traffic flow models vary widely, and some of the models have distinct modelling conceptions. In this work, some simulation-oriented models have been described:

***CONTRAM*** was the first-ever developed model presenting the aspects of mesoscopic modelling. The name of the model itself stands for the "CONtinuous TRaffic Assignment Model". Its structure is based on the link-node network, where the link behaviour of a batch of vehicles is determined by the free-flow speed on that link, or a speed/flow relation. ***DynaMIT*** (Dynamic Network Assignment for the Management of Information to Travellers) is a real-time dynamic traffic assignment software that provides traffic forecasting and travel guidance. This system has been developed since 1990's at MIT, with the goal of being able to simulate and predict the effects of real-time traffic information provided to the drivers.

***DYNASMART, FASTLANE, DTASQ.*** Another idea is based on the queue-server approach. This approach represents a road as a queuing and running carriageway. Lanes are usually not modelled. Vehicles are modelled individually and have their individual speed. At the same time, their behaviour is not modelled in detail. Vehicles run on the carriageway of the road with a speed which is defined by using macroscopic speed-density function. By reaching the downstream end, a queue server transfers vehicles to the next road segment. The advantage of this approach is connected with simulation of vehicles individually and with easy calibration of macroscopic speed/density relationships. The capacity of the servers (at nodes) is a matter of the saturation flows and their variance (estimated or calculated). In case of signal controllers, simulation servers are replaced by state-changing gates (open/closed state) according to the respective states of the signal control (green/yellow/red). Here it should be noted that the main advantage of these models is that vehicles are modelled individually, thus giving some information about the routes of travel. It is not available in the previously described models, because in these models vehicles were grouped somehow.

***AMS*** model stands for "anisotropic mesoscopic simulation" and is developed based on two intuitive traffic characteristics:

- At any time, a vehicle's prevailing speed is influenced only by the vehicles in front of it, including those being in the same or adjacent lanes.

- The influence of traffic downstream upon a vehicle decreases with the increased distance.

The above-mentioned characteristics define “anisotropic” property of the traffic flow and provide general principle for AMS model.

The traffic system in ***MEZZO*** is described by a graph with two objects: nodes and links. The nodes represent the point of traffic flow intersection and the origin and destination of traffic. The links are the road between nodes. Links are unidirectional, so if one has to simulate a bidirectional road, two links should be used. Lanes are not presented in the model separately. Usually nodes have a number of incoming and outgoing links. Links are divided into the running part and the queue part. The running part is a segment of road with free movement ability for vehicles. The queuing part represents the segment of road occupied by vehicles standing in queue.

Analysis of the existing mesoscopic models shows that currently there is lack of a unified approach, which could be used in traffic analysis research tasks. There are some applications having no distinct advantages of using classical approaches to modelling. That is why the development of new simulation approaches meant for solving specific tasks remains vitally important. The area of specific tasks could be outlined: modelling a fragment of the transport network, with a large number of transport nodes; modelling wide transport corridors (with a large distance between transport nodes); etc.

**Chapter 2** (Comparative analysis of simulation approaches)

Simulation is a powerful tool for analysis and investigation of various systems. We could emphasize the universality of this tool as the main advantage of simulation, which means the ability to model different types of the systems. Simulation branch is presented by 5 approaches; they are as follows: discrete event simulation, agent-based simulation, system dynamics, hybrid simulation and discrete rate simulation.

The *Discrete event simulation* (DES) is the paradigm, which is realized in the major part of software tools (for example, GPSS, Extend, Arena, Witness, Automod, FlexSim, Plant Simulation etc). This approach has been known since

1960s, when it was described by Geoffrey Gordon. A discrete event simulation model is defined by three properties:

- Stochastic – at least, some of the system-state variables are random.
- Dynamic – the time evaluation of the system-state variables is important.
- Discrete event – significant changes in the systems state variables are associated with an event occurring in the instance of discrete time only.

The main concepts of *Agent-based simulation* appeared only in 1990s. At present, there exist various definitions in the literature; from the practical point of view, it can be defined as essentially-decentralized, individually-centric (as opposed to system level) approach to model design. When designing an agent-based model, the modeller identifies active entities - *agents* (it can be people, companies, projects, assets, vehicles, cities, animals, ships, products etc.), defines their behaviour (driving habits, reactions, memory, states etc), introduces them into a certain environment, possibly establishes connections and runs the simulation. At present, there are only a few software products available in the market; they are RePast, Swarm, ASCAPE, NetLogo and AnyLogic.

*System Dynamics* (SD) deals with time-dependent behaviour of the managed systems with the aim of describing the system and – by using qualitative and quantitative models – grasping the idea of how information feedback governs the system behaviour; furthermore, robust information feedback structures and control policies are designed through simulation and optimisation. In fact, system dynamics is a set of differential equations. That is why the system dynamics does not deal with a particular object, but rather with aggregated sets of objects which flow from one stock to another with an intensity defined by flow variables. Currently, there is a lot of software products dealing with system dynamic approach, and we can enumerate the following ones, being the most popular: VenSim, PowerSim, iThink and AnyLogic.

*Hybrid simulation* approach is not the classical one, but it is widely used over the last few years. The main idea is to combine different approaches in one model. By simulating different parts of the system using different approaches, a developing flexibility is achieved and the model development time is reduced. There are no strict rules prescribing specific approaches to be combined, it is up to developer. The only limitation in this case is specific

features of the software used. The most well-known software, which allows building hybrid models, is AnyLogic.
The *Discrete Rate* philosophy standing behind this approach can be described with the phrase “event planning for continuous processes”. The representation of individual flow objects that reproduce persons, job orders, goods, etc. is dispensed with. The only employed members that are used in the model represent the respective quantities of objects or materials and can be modified with mathematical formula in every step of the simulation time
Mesoscopic modelling shows only discrete changes of the corresponding continuous flows. It means that flow intensity $\lambda(t)$ remains unchangeable within each time interval between flow changes. Function $\lambda(t)$ could be called slice constant function. Figure 1 presents diagrams of income and outcome flow for a simple store.

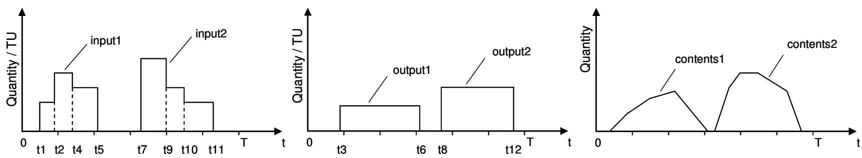



Figure 1. **Process presentations in discrete rate approach**

The right graph presents contents of the store for the given input and output flow. Since λ(t) is a piecewise constant function, the graph of the store content could be only a piecewise-linear function. The main advantages of such process representation in mesoscopic modelling are probably forecasting (in planning, calculating) certain moments of time, the contents of store and cumulative value of flow reaching the given values.
Thus, dual properties are characteristic of the mesoscopic model:

- its flow processes characterized by intensity λ(t) (as in the case of a continuous-type model);
- for processes in store and for cumulative values of flows, the future events (as in the case of models of discrete events) could be planned.

The single continuous fragments of the flow, which will be called the batches of product, could be treated as objects. The mesoscopic model features the possibility to control the path of any batch of product during its movement through the model structure. The main components used in a mesoscopic model could be mentioned here: source, funnel, and transport element. The source element is required to inject flow inside the system; the main parameter of this component is intensity. Still, it must be noted that intensity in this case is not just a constant value, but it could vary depending on time. The next and the most important element is a funnel. Funnels could be divided into two classes: single channel funnels and multi-channel funnels. Such a division allows one to simulate multi product systems. The idea of funnel is presented on Figure 2.

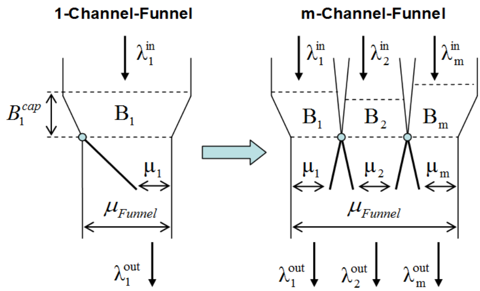



Figure 2. **Single channel funnel and multi-channel funnel**

The notation is equal for single channel and multi-channel funnel as follows:

$\lambda_i^{in}$ – input flow for the channel i;

$B_i^{cap}$ – the capacity for the channel i;

$B_{funnel}^{cap}$ – the capacity of the funnel;

$B_i$ – the current level of product for the channel i;

$\mu_i$ – the processing rate for channel i;

$\mu_{funnel}$ – the processing rate for funnel;

$\lambda_i^{out}$ – the output flow from channel i.

The following restrictions are defined as follows:

$$B_i \le B_i^{cap}, \sum B_i^{cap} \le B_{funnel}^{cap},$$

$$\lambda_i^{out} \le \mu_i, \sum \mu_i \le \mu_{funnel}.$$

The output flow could be calculated using the following equation:

$$\lambda_i^{out} = \begin{cases} 0, & \lambda_i^{in} = 0 \text{ and } B_i = 0 \\ \lambda_i^{in}, & \lambda_i^{in} > 0 \; and \; \lambda_i^{in} \leq \mu_i \text{ and } B_i = 0 \\ \mu_i, & B_i > 0 \end{cases}$$

The funnel level of product in channel could be obtained by using the following equation:

$$B_i(t + \Delta t_j) = B_i(t) + \left(\lambda_i^{in}(t) - \lambda_i^{out}(t)\right) \cdot \Delta t_j$$

It must be noted that parameters like $\lambda_i^{in}$ and $\mu_i$ can be changed every $t_j = t_{j-1} + \Delta t_j$. It means that these parameters are time dependent and could be rewritten in the following way $\lambda_i^{in}(t)$ and $\mu_i(t)$.

The step value could be fixed or variable. The type of step which should be used in the model depends on the type of system simulated and the processes running inside the simulated systems. Scheduling of the events is the most important in both cases. The Figure 3 presents an example of event scheduling for continuous processes in a funnel. The first two events (event 1 and event 2) are assumed to be independent of the system's current state.

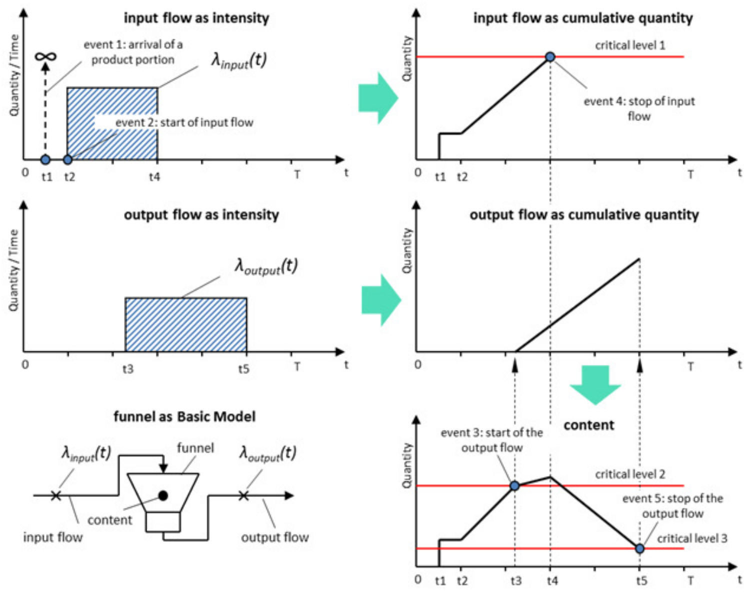



Figure 3. **Event scheduling for continuous processes**

Specific conditions are specified for all the other events:

- Event 3: The funnel's output flow can only start when its stock has reached the critical level 2.
- Event 4: The funnel's input flow is terminated when the entire quantity of products in the flow has reached the critical level 1.
- Event 5: The funnel's output flow is terminated when its stock has reached the critical level 3.

Times t3, t4 and t5 can be calculated precisely and entered into the simulators' chain of future events. Ultimately, only five events must be processed in the variable time interval Δt. In terms of performance, the advantage of this type of time advance over a fixed time step Δt is obvious.

As it was written before, two possible time step types could be selected for mesoscopic modelling: fixed time step and variable time step. The use of variable time step gives more flexibility to the model and, as a result - some more exact output result at the end, on the one hand, and the fact that a fixed time step is simpler in realization – on the other hand. The Figure 4 shows the general difference in both cases: application of fixed time step and use of variable time step.

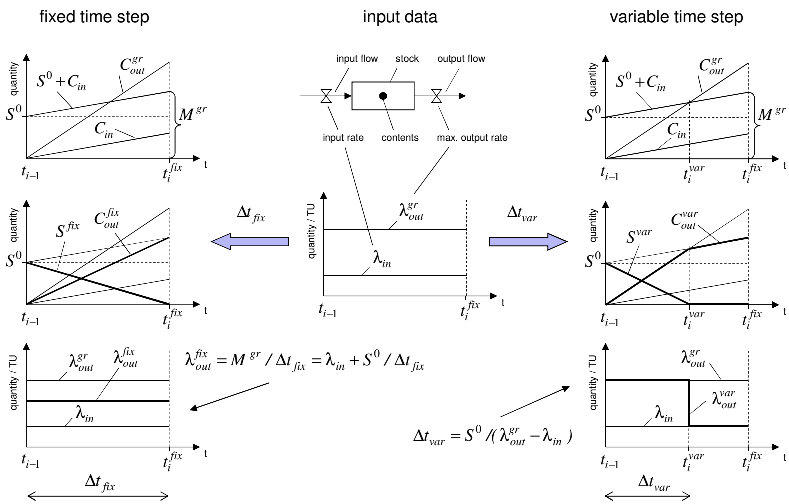



Figure 4. **Mesoscopic modelling by fixed and variable time step**

The main feature of mesoscopic modelling is the point that all intensities of the flows $\lambda(t)$ within each step $\Delta t$ of the model time *t* stay permanent. At the same time, a step value $\Delta t$ could be given a fixed value or should be calculated for each new step. This situation will be described below on the basis of simple stock (see Figure 4).

It is expected that current time of the process is $t_{i-1}$. The following values are given:

- the level of stock $S(t_{i-1})$ in time $t_{i-1}$, equal to $S^0$;
- fixed time step $\Delta t_{fix}$;
- permanent intensity of the input flow $\lambda_{in}$;
- maximum value of the intensity of the output flow $\lambda_{out}^{gr}$.

In case of a fixed time step, the next moment of time is determined using the following formula:

$$t_i^{fix} = t_{i-1} + \Delta t_{fix} \tag{1}$$

If output flow of stock will not be taken into account, the level of stock for time $t_i^{fix}$ will be equal to:

$$S\left(t_i^{fix}\right) = S^0 + C_{in}\left(t_i^{fix}\right) = S^0 + \lambda_{in}\Delta t_{fix} = M^{gr} \tag{2}$$

If maximum value of intensity of the output flow $\lambda_{out}^{gr}$ is so small, that the following condition is true

$$C_{out}^{gr}\left(t_i^{fix}\right) = \lambda_{out}^{gr}\Delta t_{fix} \leq M^{gr} \tag{3}$$

then the real intensity of the output flow $\lambda_{out}^{fix}$ within all the intervals will be equal to $\Delta t_{fix}$. Further, the case with condition 3 not being true will be described. This means, that the level of stock could be decreased to 0 until the time moment $t_i^{fix}$. Intensity of the output flow $\lambda_{out}^{fix}$ in this case cannot be $\lambda_{out}^{gr}$ within the time interval $\Delta t_{fix}$, because it will lead to negative values of the level of stock at the time $t_i^{fix}$.

Figure 4 shows the following two cases:

- next moment of time for the process $t_i^{fix}$ is determined by fixed time step $\Delta t_{fix}$;

- next time step of the process $\Delta t_{var}$ is determined by moment of time $t_i^{var}$, for which event will occur (the level of stock will reach 0).

For the fixed step $\Delta t_{fix}$, within the time interval any changes in flows could not be reflected. It is assumed that at the end of time interval $\Delta \mathrm{t_{fix}}$ the cumulative volume of output flow will be $M^{gr}$. This means that fixed intensity $\lambda_{\mathrm{out}}^{\mathrm{fix}}$ could be determined by the following formula:

$$\lambda_{out}^{fix}\Delta t_{fix} = M^{gr} \tag{4}$$

From equations 3 and 4 it follows:

$$\lambda_{out}^{fix} = \frac{M^{gr}}{\Delta t_{fix}} = \frac{\left(S^0 + \lambda_{in}\Delta t_{fix}\right)}{\Delta t_{fix}} = \lambda_{in} + S^0/\Delta t_{fix} \tag{5}$$

Permanent intensity $\lambda_{\mathrm{out}}^{\mathrm{fix}}$ also means that level of stock $S^{fix}(t)$ within the interval will be evenly (linearly) decreased to 0. In this case, no real moment of time $t_i^{var}$ when stock will be empty can be determined.

On the other hand, modelling with variable time step $\Delta \mathrm{t_{var}}$, is based on preliminary calculations of moments of time $t_i^{var}$, then the determined conditions are true. In this example these conditions are:

$$S^0 + \lambda_{in}\Delta t_{var} = \lambda_{out}^{gr}\Delta t_{var} \tag{6}$$

From formula 6 it follows:

$$\Delta t_{var} = S^0/\left(\lambda_{out}^{gr} - \lambda_{in}\right) \tag{7}$$

and

$$\mathrm{t}_i^{var} = t_{i-1} + \Delta t_{var} \tag{8}$$

Thus, using modelling with variable time step, two time intervals: $(t_{i-1}, t_i^{var})$ and $\left(t_i^{var}, t_i^{fix}\right)$ were constructed. During the first interval real intensity $\lambda_{out}^{var}$ is equal to maximum value of $\lambda_{out}^{gr}$ , but during the second one equals to $\lambda_{in}$. The level of stock decreases at the end of the first interval till 0 and stays at this level within the whole interval $\left(t_i^{var}, t_i^{fix}\right)$.

All the above-described simulation approaches could be separated into groups. The separation could be based on detail level. Discrete event simulation and agent-based simulation are mainly used at microscopic level. The system dynamics approach could be applied at macroscopic level. And, finally, the discrete rate approach deals with mesoscopic level. It could be seen from Figure 5 that the application of macroscopic approaches is often connected with such operation as data aggregation; that is why the final results are frequently not so exact. The application of microscopic approaches is connected with decomposition operation. And due to this, model construction and experimentation with it, is a process of time consumption.

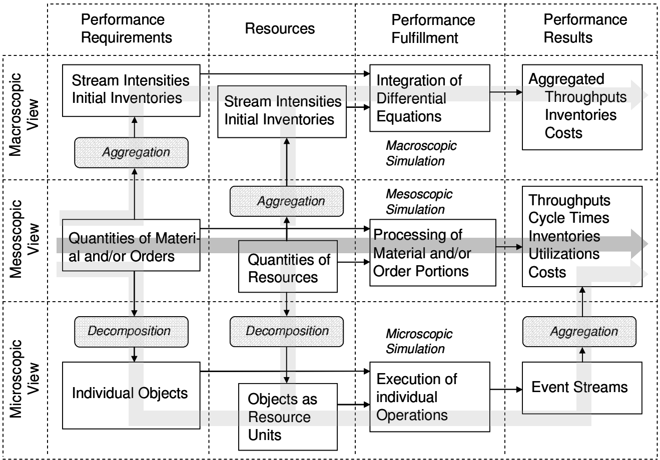



Figure 5. **Relationship between levels**

**Chapter 3** (Development of the concept of a mesoscopic discrete rate traffic simulation model)

As it was mentioned above, mesoscopic concepts are mainly used for simulation of logistic systems. That is why mesoscopic approach is primarily formulated for flow logistics systems. The goal of this chapter is to update DR approach and to transform it for traffic flow simulation. Traffic flow simulation is a very specific area of application of simulation due to the existing difference between processes inherent in traffic and in logistic systems. In this chapter, two mathematical models were formulated: the first one is meant for an uncongested network, and the second one for a congested network. Most generally, the model for a congested network should be treated as possible queues in the transport systems are taken into account.

*A. Uncongested network.* Let us consider a network consisting of two signal-controlled crossroads linked together by the road. The Figure 6 presents an example of such a network with the notations used here to describe mathematical model for traffic flow simulation. As it is seen from Figure 6, a number of input flows from different directions marked by $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ exist within the transport system. At the same time, there exist intensities of the output flows marked by $\beta_1, \beta_2, \beta_3, \beta_4$. Comparing to logistics systems, a very complex interaction between flows could be observed in this case. This interaction is determined by splitting input flows by different directions and, at the same time, some control mechanism should be applied to prioritise the flows. To show the flows interaction, Figure 7 is represented with a higher detail level by using Figure 6, which explains interaction between flows.

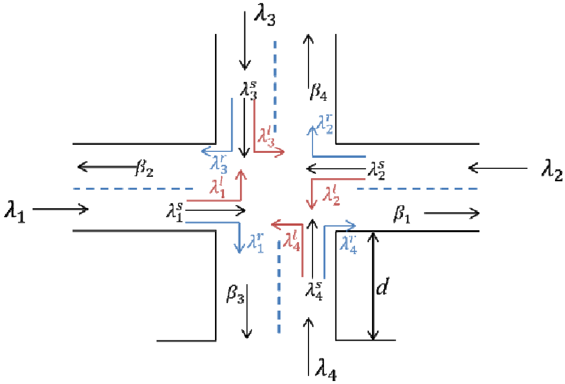



Figure 6. **Example of transport network**

The transport network shown on Figure 6 could be also presented according to the DR notation with funnels and transporting element, as it is shown on Figure 7. As it could be seen, the transport network using 5 funnels and 1 transporting item is described. The next description of the used notation could be given:

$\lambda_i$ – input intensity of the flow from direction *i=1..5 (*used units: PCU per time unit);

$\beta_i$ – output flow value from direction *i=1..5 (*used units: PCU per time unit);

$\lambda_i^l, \lambda_i^s, \lambda_i^r$ – intensity of the flow for the turns (*l-left; s-straight; r-right*) from direction *i=1..5* (used units: PCU per time unit);
$b_i^l$, $b_i^s$, $b_i^r$ - queue length for the turns (*l-left; s-straight; r-right*) from direction *i=1..5* (used units: PCU);
$\mu_i^l$, $\mu_i^s$, $\mu_i^r$ - the capacity for the turns (*l-left; s-straight; r-right*) from direction *i=1..5* (used units: PCU per time unit);
$\beta_i^l$, $\beta_i^s$, $\beta_i^r$ - output flow rate for the turns (*l-left; s-straight; r-right*) from direction *i=1..5* (used units: PCU per time unit);
$\beta_i$ – total output flow to direction *i=1..5* (used units: PCU per time unit);
$B_5^{cap}$ - the maximum value of queue length for direction 4 (used units: PCU).

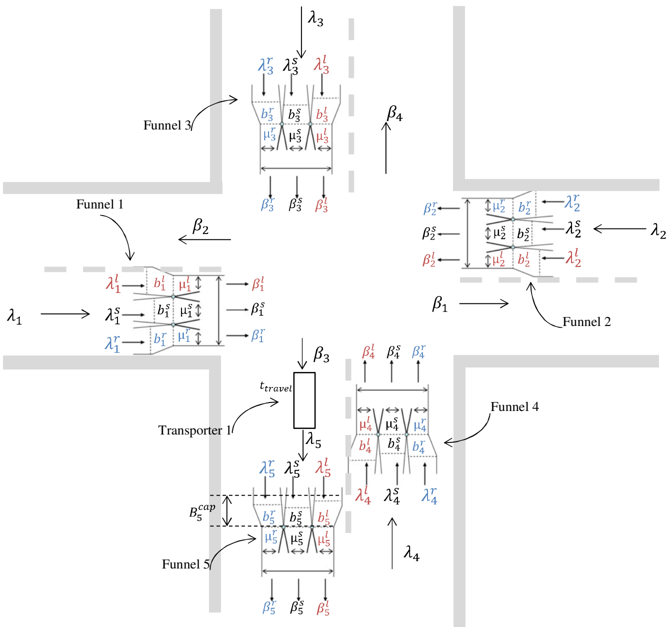



Figure 7. **Transport network in Discrete Rate notation**

The following equations could be written, which define intensity of the flow by direction and by turns:

$$\begin{cases} \lambda_i^r(t) = \lambda_i(t)p_i^r \\ \lambda_i^s(t) = \lambda_i(t)p_i^s \\ \lambda_i^l(t) = \lambda_i(t)p_i^l \\ p_i^r + p_i^s + p_i^l = 1 \end{cases} \quad (9)$$

where $p_i^r, p_i^s, p_i^l$ – a probability of turns (*l-left; s-straight; r-right*) from direction *i=1..5;*
$t$ – current time.

$$\begin{cases} \beta_1(t) = \beta_1^s(t) + \beta_4^r(t) + \beta_3^l(t) \\ \beta_2(t) = \beta_2^s(t) + \beta_3^r(t) + \beta_4^l(t) \\ \beta_3(t) = \beta_3^s(t) + \beta_1^r(t) + \beta_2^l(t) \\ \beta_4(t) = \beta_4^s(t) + \beta_1^r(t) + \beta_2^l(t) \\ \beta_5(t) = \beta_5^s(t) + \beta_5^r(t) + \beta_5^l(t) \end{cases} \quad (10)$$

$$\begin{cases} \mu_i^r(t) = f_i^r(\Delta t(t)) \\ \mu_i^s(t) = f_i^s(\Delta t(t)) \end{cases} \quad (11)$$

where $\Delta t(t)$ – time step within time *t* (in this demonstration equal to the duration of green phase (for simplification $t_{green}$) is equal for all directions and all crossroads;
$f_i^n()$ – passing function which determine throughput capacity from direction *i=1..5* and turn $n \in (l, s, r)$.

The form of the above-mentioned function could be empirically found during observations of real traffic; this task was solved in chapter 5.

$$\beta_{i\in(1,2,4,5)}^s(t) = \begin{cases} 0,\ \lambda_i^s(t) = 0\ and\ b_i^s(t) = 0 \\ \lambda_i^s(t), \lambda_i^s(t) > 0\ and\ \lambda_i^s(t) \le \mu_i^s\ and\ b_i^s(t) = 0 \\ \mu_i^s, b_i^s(t) > 0 \end{cases} \quad (12)$$

$$\beta_{i\in(2,3,4,5)}^r(t) = \begin{cases} 0,\ \lambda_i^r(t) = 0\ and\ b_i^r(t) = 0 \\ \lambda_i^r(t), \lambda_i^r(t) > 0\ and\ \lambda_i^r(t) \le \mu_i^r\ and\ b_i^r(t) = 0 \\ \mu_i^r, b_i^r(t) > 0 \end{cases} \quad (13)$$

$$\begin{cases} \mu_1^l = f_1^l\left(t_{green} - f_2^{s^{-1}}\left(\beta_2^s(t)\right)\right) + h \\ \mu_2^l = f_2^l\left(t_{green} - f_1^{s^{-1}}\left(\beta_1^s(t)\right)\right) + h \\ \mu_3^l = f_3^l\left(t_{green} - f_4^{s^{-1}}\left(\beta_4^s(t)\right)\right) + h \\ \mu_5^l = f_5^l(t_{green}) + h \end{cases} \tag{14}$$

where $h$ – additional capacity, explained by crossing of the crossroad during yellow colour of traffic light;

$f_i^{n^{-1}}()$ – inverse passing function, which determines the time required for passing a crossroad.

$$\beta_{i\in(1,3,5)}^l(t) = \begin{cases} 0,\ \lambda_i^l(t) = 0\ and\ b_i^l(t) = 0 \\ \lambda_i^l(t), \lambda_i^l(t) > 0\ and\ \lambda_i^l(t) \le \mu_i^l\ and\ b_i^l(t) = 0 \\ \mu_i^l, b_i^l(t) > 0 \end{cases} \tag{15}$$

$$\Delta b_5(t) = B_5^{cap} - b_5^r(t) - b_5^s(t) - b_5^l(t) \tag{16}$$

$$\beta_1^r(t) = \\ = \begin{cases} 0,\ \lambda_1^r(t) = 0\ and\ b_1^r(t) = 0 \\ \lambda_1^r(t), \lambda_1^r(t) > 0\ and\ \lambda_1^r(t) \le \mu_1^r\ and\ b_1^r(t) = 0\ and\ \lambda_1^r(t) \le \Delta b_5(t) \\ \mu_1^r, b_1^r(t) = 0,\ \mu_1^r \le \Delta b_5 \\ \Delta b_5\ , b_1^r(t) = 0 \end{cases} \tag{17}$$

$$\beta_3^s(t) = \\ = \begin{cases} 0,\ \lambda_3^s(t) = 0\ and\ b_3^s(t) = 0 \\ \lambda_3^s(t),\ \lambda_3^s(t) > 0\ and\ \lambda_3^s(t) \le \mu_3^s\ and\ b_3^s(t) = 0\ and\ \lambda_3^s(t) \le \Delta b_5(t) \\ \mu_3^s, b_3^s(t) = 0, \mu_3^s \le \Delta b_5 \\ \Delta b_5\ , b_3^s(t) = 0 \end{cases} \tag{18}$$

$$\mu_2^l = f_2^l\left(t_{green} - f_1^{r^{-1}}\left(\beta_1^r(t)\right)\right) + h \tag{19}$$

$$\beta_2^l(t) = \\ = \begin{cases} 0,\ \lambda_2^l(t) = 0\ and\ b_2^l(t) = 0 \\ \lambda_2^l(t),\ \lambda_2^l(t) > 0\ and\ \lambda_2^l(t) \le \mu_2^l\ and\ b_1^r(t) = 0\ and\ \lambda_2^l(t) \le \Delta b_5(t) \\ \mu_2^l, b_2^l(t) = 0, \mu_2^l \le \Delta b_5 \\ \Delta b_5\ , b_2^l(t) = 0 \end{cases} \tag{20}$$

*B. Congested network.* The second model proposed for a congested network simulation is generally based on the previous model, but takes into account the length of the road between crossroads, queue growing rate, and travel time between crossroads. To make these options available, the model for uncongested network should be updated in the following way (see Figure 8).

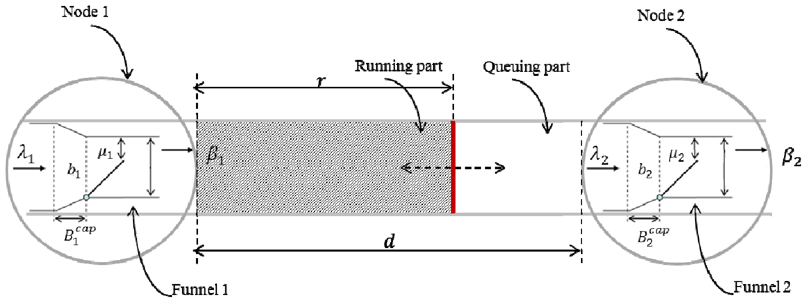



Figure 8. **Model for congested network**

Description of the following notations could be done:
*d* – length of the road between crossroads (measured in PCU);
*r* – length of the running part of the road (measured in PCU);
*d-r* – length of the queuing part of the road (measured in PCU);
$\lambda_1$ – intensity of income flow for funnel 1 (measured in PCU per time unit);
$\lambda_2$ – intensity of income flow for funnel 2 (measured in PCU per time unit);
$B_1^{cap} = \infty$ – maximum length of the queue in $1^{st}$ funnel (measured in PCU);
$B_2^{cap} = d$ – maximum length of the queue in $2^{nd}$ funnel (measured in PCU);
$b_1$– length of queue in the first funnel (measured in PCU);
$b_2$ – length of queue in the second funnel (measured in PCU);
$\mu_1$ – capacity for first funnel (measured in PCU per time unit);
$\mu_2$ – capacity for second funnel (measured in PCU per time unit);
$\beta_1$ – outflow intensity for first funnel (measured in PCU per time unit);
$\beta_2$– outflow intensity for second funnel (measured in PCU per time unit).
There is no need to describe the way of processing traffic flow passing through the funnels, as it was described in the previous subchapter; that is why some more attention will be paid now to the mechanism, which allows modelling the congested network. The main problem of the previous model is the fact that no

reference to the growing queue of the vehicles and taking up a part of the road was made. That is why the following mechanism is proposed in this model. The road between the crossroads (let's call it "a link") is divided into two parts: the running and the queuing ones. The division of roads into two parts is dynamic, it means that during simulation a running part could be increased or decreased depending on queuing part. The length of the queuing part is equal to the length of the queue of 2nd funnel. This could be written as the following:

$$r(t) = d - b_2(t) \tag{21}$$

The running part of the link is used for the movements. A movement in this model is defined by the travelling time that could be calculated by using one of volume delay function (VDF) by the following example:

$$\begin{cases} t_{cur} = t_0(1 + a \cdot sat^b), if\ sat < sat_{crit} \\ t_{cur} = t_0(1 + a \cdot sat^b) + (q - q_{max})d, if\ sat \geq sat_{crit} \end{cases}$$
$$sat = \frac{q}{q_{max}c} \tag{22}$$
$$sat_{crit} = 1$$

where $t_0$ – free flow travel time (measured in time units);
$q$ – traffic quantity in running part (measured in PCU);
$q_{max} = r$ – capacity (measured in PCU);
$t_{cur}$– travel time in loaded network (measured in time units);
$a, b, c, d$ – parameters of the VDF.

The free flow travel time $t_0$ could be defined by the following equation:

$$t_0 = \frac{r}{v},$$

where $v$ – speed on link.

**Chapter 4** (Comparing the developed approach with microsimulation. Case studies.)

The goal of the examples proposed in this chapter is to demonstrate the way the transport models could be constructed on the basis of DRTRM. Most of the focus is on validation of the model outputs by applying statistical methods (classical statistics tests, Naive, Novel tests etc.)

*Case-study 1: Simulation of crossroad*

The modelling object is a symmetric crossroad with traffic light control. Transport flows are created in sources 1 to 4. They can pass the crossroad by using the following directions: right (r), straight (s) and left (l). Two opposite sources have their green phase at the same time. During this time the two remaining sources have their red phase. That means that they do not interfere with each other. The modelling task is to estimate the dynamics of all queues. Transport flows and traffic lights phases are given.

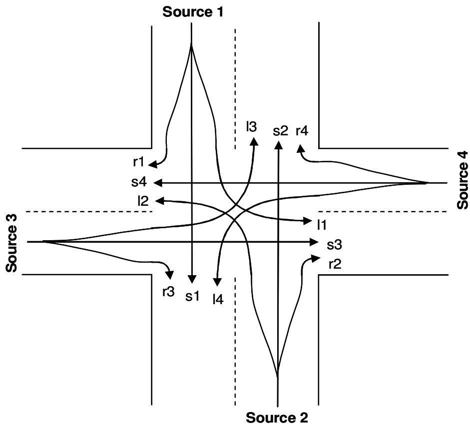



Figure 9. **Conceptual model of the crossroad**

Random values are used for the determination of all 12 incoming flows. An empirical function (see Figure 9) is used to create a more realistic process of crossroad passing. This function was estimated through direct observation of real crossroad passing processes. This function can be used for all directions. The function is used in the model as direct and as inverse function. Figure 10 shows that within the first 25.5 seconds of a traffic light cycle a vehicle flow with the length *q1*=122 m can pass the crossroad, and within the first 32.5 seconds - the flow of *q2*=185 m.

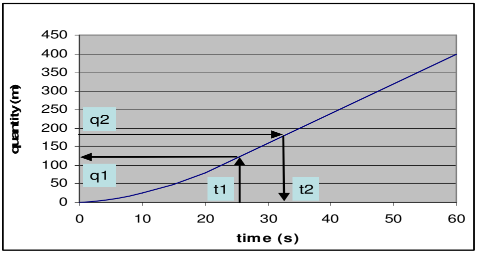


Figure 10. **Dynamic of vehicle flow during crossroad passing**

The principal structure of the crossroad model is presented on Figure 11. The model consists of four autonomic components, because no direct relationships exist between the traffic flows of the four directions. Each component has three parallel channels. The channels generate, delay, and release traffic flows. The delay and the release are realized by a multichannel funnel described above. The content of each channel of the funnel is numerically equal to the length of the queue. The control component of the model (Flow Control) defines the quantity of vehicles, which can pass the crossroad in each traffic light cycle in different directions.

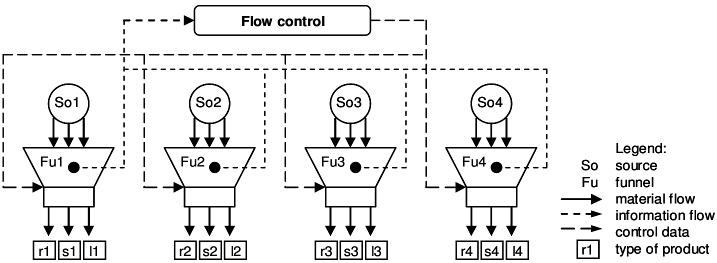


Figure 11. **Structure of the mesoscopic model**

The model proper was developed in Microsoft Excel 2003 using Visual Basic for Application (VBA). The selection of development tool implies a possibility of using internal spreadsheets, internal programming languages, and internal visualization tools as graphs.

Table 1 presents the outcomes of modelling 20 cycles. The frames “input (sum)” and “output (sum)” show the total length values of funnel entrance and funnel exit. The data within the frame "queue (maximum)" present the maximal lengths of the queues during model execution. The queue lengths are changing during a traffic light cycle.

Table 1.

**Output data of the mesoscopic model of a crossroad**

| Cycle number: 20 of 20 | | | Time (s): 1000 | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Funnel 1** | | | | | | | | | | | |
| input (sum) | | | | output (sum) | | | | queue (maximum) | | | |
| right | straight | left | total | right | straight | left | total | right | straight | left | total |
| 330.9 | 1115.9 | 187.5 | 1634.3 | 335.9 | 1108.4 | 188.2 | 1632.5 | 12.6 | 69.3 | 18.1 | 96.3 |
| **Funnel 2** | | | | | | | | | | | |
| input (sum) | | | | output (sum) | | | | queue (maximum) | | | |
| right | straight | left | total | right | straight | left | total | right | straight | left | total |
| 352.4 | 1117.0 | 161.6 | 1630.9 | 357.4 | 1127.0 | 159.3 | 1643.7 | 15.4 | 50.4 | 15.2 | 72.1 |
| **Funnel 3** | | | | | | | | | | | |
| input (sum) | | | | output (sum) | | | | queue (maximum) | | | |
| right | straight | left | total | right | straight | left | total | right | straight | left | total |
| 275.1 | 886.8 | 159.9 | 1321.8 | 280.1 | 896.8 | 164.9 | 1341.8 | 10.9 | 34.5 | 12.8 | 54.9 |
| **Funnel 4** | | | | | | | | | | | |
| input (sum) | | | | output (sum) | | | | queue (maximum) | | | |
| right | straight | left | total | right | straight | left | total | right | straight | left | total |
| 345.4 | 1173.1 | 186.2 | 1704.8 | 350.4 | 1183.1 | 191.2 | 1724.8 | 16.8 | 54.6 | 15.1 | 86.4 |

Also the dynamics of all 4 queues could be presented by Figure 12.

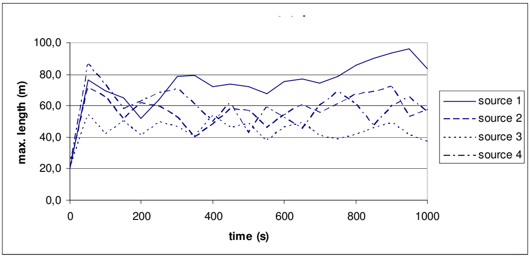



Figure 12. **Dynamics of queues of incoming flows**

*Case-study 2: Simulation with two connected crossroads*

The modelling object is a fragment of transport network. The conceptual model is presented on Figure 13.

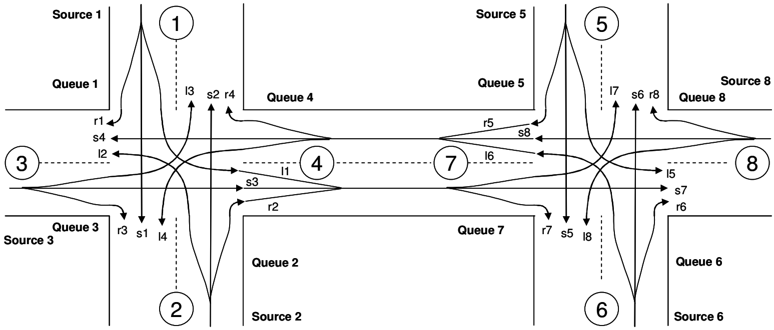



Figure 13. **Conceptual model of the transport network fragment**

The fragment consists of two symmetric traffic-light signalised crossroads, which are connected with the road which is a part of the model. The vehicle flow enters the network from 6 zones, which are enumerated like 1, 2, 3, 5, 6 and 8. Each income flow is divided into three moving directions: right (*r*), straight (*s*) and left (*l*). The geometry of the crossroads is constructed in such a way that vehicles entering the network from one zone and belonging to one direction *r*, *s* and *l*, can reach and pass the crossroad independently from the other directions. Only the vehicles turning left (flow *l*), depend on the duration of flow *s*, which passes the crossroad straight in the counter lane, during the green phase of traffic light.

All model construction issues are the same as the model constructed in the first case-study. That is why, not focusing on model development any more, we would rather go ahead and present only the issue of the proposed model validation results. To validate the constructed mesoscopic model, we are using simulation on microscopic level. According to the conceptual model (see Figure 13), a microscopic model of the crossroads in professional simulation software PTV VISION VISSIM has been developed. Subsequently, visual validation and validation approaches based on statistical methods were used for the purpose.

*Animation-based validation:* according to the observed animation of the simulation process in microscopic model, it could be concluded that a mesoscopic model on qualitative level represents microscopic level.

*Comparison of Queue dynamics:* According to the observation of queue dynamics, it could be concluded that mesoscopic model on qualitative level represents microscopic level.

*Test for homogeneity:* The Student's *t* test and Mann-Whitney *u* test were performed. As some of the data does not comply with normal distribution, the *t* test will not be performed for queue 7, queue 6 and queue 3, but still *u* test will be completed. The obtained results prove, that hypothesis about data homogeneity could not be rejected with α=0.05, so mesoscopic model is valid.

*Confidence interval test:* The results of application confidence interval test show that there are no significant difference in average between values obtained from microscopic model and mesoscopic model with α=0.05.

*Naive test:* The application allows us to conclude, that for most data sets the models are valid, with the exception of the Queue 4 and Queue 7. The analysis of the reasons for the Naive test failure is connected with the fact that Naive test requires n.i.i.d. For Queue 7, the test on normality fails. For Queue 4 it must be noted that $F_{naive}$ value is very close to the AR.

*Novel test:* The application of the Novel test for data gives the following results: for Queue 1, Queue 3, Queue 5 the null hypothesis is not rejected and for all other data sets $F_{novel}$ is not accepted.

To sum up all the obtained results during validation procedure, the following table could be constructed and conclusion could be made that the mesoscopic model could be treated as valid in general.

Table 2.

**Summary of validation results**

| Data set | Qualitative validation (animation) | Test for homogeneity | Confidence interval test | Naive test | Novel test |
|---|---|---|---|---|---|
| *Queue 1* | Valid | Valid | Valid | Valid | Valid |
| *Queue 2* | Valid | Valid | Valid | Valid | Not valid |
| *Queue 3* | Valid | Valid | Valid | Valid | Valid |
| *Queue 4* | Valid | Valid | Valid | Not valid | Not valid |
| *Queue 5* | Valid | Valid | Valid | Valid | Valid |
| *Queue 6* | Valid | Valid | Valid | Valid | Not valid |
| *Queue 7* | Valid | Valid | Valid | Not valid | Not valid |
| *Queue 8* | Valid | Valid | Valid | Valid | Not valid |

**Chapter 5** (Mesoscopic simulation of an urban transport corridor)

This chapter demonstrates an example of the application of proposed DRTRM model for traffic flow simulation on the existing object with real data, taking into account traffic lights located in the simulated area. The object of the research is the urban transport corridor located in Riga city and consists of 10 crossroads. This transport corridor connects the city centre and residential districts inside and outside the city. The length of the investigated part of the transport corridor is approximately 1500 meters. The transport corridor scheme is presented on Figure 14.

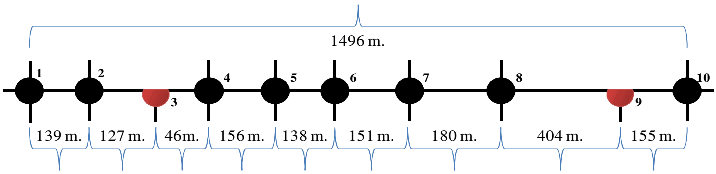



Figure 14. **Scheme of Transport Corridor**

To simplify reference to crossroads within the transport corridor, all of them are numbered. Moreover, it should be noted that the direction from city centre goes from left to right. The bulk of the crossroads are controlled by traffic lights, except for the crossroads 3 and 9. The data on traffic lights shows the duration of cycle and the duration of each light. The volumes of traffic have been obtained during traffic counts. The traffic counts are estimated during morning peak hours from 8:00-9:00 a.m. in October, 2010. During traffic counts, a number of vehicle types are differentiated: bicycles, motorcycles, passenger vehicles, light cargo trucks, HGV, buses, single trolleybuses, and twin trolleybuses. The mesoscopic approach in the current formulation does not take into account types of vehicles; that is why all collected data have been aggregated into PCU (passenger car unit).
Finally, the following general information about the transport corridor should be stated:

- allowed speed across transport corridor is 50 km/h;
- transport corridor has two lanes per direction;

- all public transport stops are made outside the main roads and are located in pockets;
- traffic lights are managed for creating a green wave across the entire transport corridor.

The main task is connected with modelling of the described transport corridor and the definition using the simulation results level of service (LOS) for each crossroad. At this point, it is necessary to emphasize that LOS will be calculated based on the average delay value on crossroad according to HCM standard. Using the data collected during real observation of how vehicles pass the crossroad, a form of passing function has been determined. To obtain the form of passing function, 6 different regression models are constructed based on the collected data. Analysing the obtained regression models the decision on passing function has been made (see Equation 23), and will hereinafter be used in simulation model.

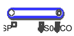
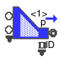
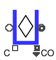
$$q^* = -1.1479 + 0.794 * t - 0.01113 * t^2 + 0.00026 * t^3 \qquad (23)$$

where $q^*$ – estimated volume of traffic;
$t$ – time.

For simulation model construction, ExtendSim software was used. However, not all of the blocks of DR library are useful for transport model construction. Table 3 demonstrates the role of DR library blocks in transport modelling.

Table 3.

**Main function of blocks in transport model**

| Block | Name | Function in transport model |
|---|---|---|
|  | Convey flow | Could be used to simulate a movement between two geographical points (at example between two crossroads). |
|  | Diverge | Could be used to simulate a splitting of the transport flow by different direction (at example on crossroads turning left, turning right, moving forward). |
|  | Merge | Could be used to merge traffic flows together. |
|  | Sensor | Could be used as the main source of information for controlling flows and to control flow interaction. |
|  | Tank | Could be used as a source and a sink. Also could be used to represent the road capacity. |

| | | |
|---|---|---|
|  | Valve | Controls, monitors, and transfers traffic flow. |

The hierarchical structure of the model was created in ExtendSim application. That is why custom library blocks have been created to simplify the process of model development: they are called "node_sig" and "node". These blocks represent crossroads with different management strategy:

- Signalised crossroads (node sig) – the crossroads controlled by traffic light with a definite length of cycle. This group includes 8 crossroads (crossroad numbers: 1, 2, 4, 5, 6, 7, 8 and 10).
- Non-signalised crossroads (node) – the crossroads not controlled by traffic light. This group includes only 2 crossroads (crossroads: 3 and 9).

The general high-level part of the model is presented on Figure 15. The example of block structure for it could be seen on Figure 16.

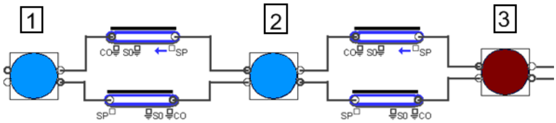



Figure 15. **Example of Constructed General High-level Model**

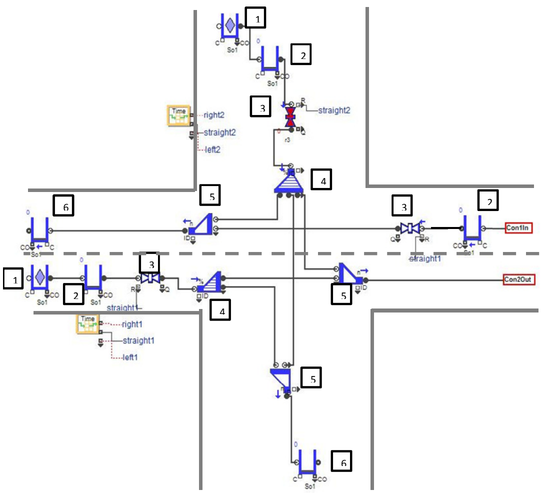



Figure 16. **Example of Internal Structure of the Block "node_sig"**

The internal structure of block "node_sig" for the 1st crossroad consists of 14 main and 2 additional blocks. Some additional blocks are required to simulate the traffic light operation. The main blocks define the behaviour of the traffic flow.

Finally, the results obtained from validated microscopic of the same part of the transport corridor, and those obtained from mesoscopic model, have been compared. The comparison results could be observed in Table 4.

Table 4.

**Delay Times and LOS Comparison**

| Crossroad Number | Microscopic Model | | Mesoscopic Model | |
|---|---|---|---|---|
| | LOS | Average delay time (s) | LOS | Average delay time (s) |
| 1 | B | 14.5 | B | 18.6 |
| 2 | B | 13.8 | B | 17.5 |
| 3 | A | 1.6 | A | 1.2 |
| 4 | B | 17.3 | B | 17.6 |
| 5 | B | 18.1 | C | 21.6 |
| 6 | B | 11.2 | B | 14.3 |
| 7 | C | 20.6 | C | 30.8 |
| 8 | C | 31.2 | D | 45.5 |
| 9 | A | 2.1 | A | 1.2 |
| 10 | D | 41.5 | E | 55.6 |

As it can be seen, notwithstanding the difference in volumes that constitutes 20% on average, LOS for crossroads is mostly matched. It should be noted of course that the delay time is somewhat different with all the crossroads, and sometimes this difference does not influence the LOS, except for the LOS related to crossroads 10, 8, and 5. For crossroad 10, the difference is equal to 14 seconds. For the numbers 8 and 5, the difference is not so significant. Essentially, the behaviour of traffic flow in the mesoscopic model is very close to real situation in this urban transport corridor. The difference in the output data can be explained by higher level of abstraction of the mesoscopic model. At the same time, the speed of development of mesoscopic model is 3 times less.

In general, the significant difference in development time is connected with a simplification of the network representation at mesoscopic level. At the same time, the difference between output data is not significant. The main advantages of the mesoscopic approach are: a significant decrease of the development time and expectable precessions of the output results. Detailed results of comparison between development and experimentation issues in microscopic and mesoscopic level could be seen in Table 5.

Table 5.

**Development and experimenting time for micro- and mesoscopic models**

| **Development and experimentation issues** (min) | **Microscopic** | **Mesoscopic** |
|---|---|---|
| Transport network implementation | 175 | 60 |
| Implementation of traffic lights | 60 | 30 |
| Conflict areas and priority rules implementation | 115 | 60 |
| Movement routes implementation | 30 | 30 |
| Traffic flow implementation | 30 | 60 |
| Time spend on experimentation | 350 | 10 |
| **Total implementation and experimentation time** | **760** | **250** |

## MAIN RESULTS OF THE THESIS

The concept of new mesoscopic traffic simulation model, which is based on discrete rate approach, is developed as the central part of the promotion work. The proposed discrete rate traffic reference model has been tested in a series of experiments using artificial and real data. As a result, the data obtained during these experiments allow us to conclude that the proposed concept could be a useful tool for transport planners and researchers in the field of traffic flow analysis. The following tasks have been solved, and the following results are obtained:

1. The review of the current and the future role of simulation models in transportation sphere has been performed; this allows one to conclude that there will be a high demand for the simulation in future as it is a powerful and exact tool for traffic flow analysis.
2. The analysis of the existing traffic analysis tools and their role has been carried out with a detailed description; this allows one to show the place of simulation models among different kinds of traffic tools; it is shown that traditional simulation methods are based on microscopic

and macroscopic approaches, which are characterized by the existence of certain non-removable disadvantages.

3. It has been found out that some known attempts to develop models combining positive characteristics of microscopic and macroscopic models, did not lead yet to the development of a new, well-defined class of models which are usually called mesoscopic; as a rule, these models are only an arbitrary combination of microscopic and macroscopic models; a review of the currently existing mesoscopic model has been performed.
4. The choice of a relatively new paradigm of flow systems, which is called the discrete rate approach, has been justified as a base for the development of mesoscopic models of traffic systems; an event planning opportunity was studied with respect to piecewise continuous processes, with the modelling being based on discrete rate approach; it is stated that the proposed event planning significantly accelerates the processing of flow systems mesoscopic models.
5. The discrete rate traffic reference model (DRTRM) is formulated and developed in mathematical form, showing the main ideas postulated in a proposed new mesoscopic traffic simulation model.
6. The traffic flow model development methodology was developed on DRTRM; some examples of the methodology application are described based on the demonstrative model of complex crossroads and the model of a real system.
7. Based on the data obtained from experiments, a validation of the developed models has been performed by using different methods, both qualitative and quantitative. Validation results prove that models developed by using DRTRM are valid; it is identified that practical benefits arising from the use of the new class of mesoscopic models lead to decrease of model development time and model processing time.
8. The example of using the proposed concept with respect to a real object located in Riga city has been presented, with a comparison of the real data obtained during the survey.

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