**“Traffic modelling and simulation”**

**Syllabus CT.04**

**Prof. Kyandoghere Kyamakya**

**Prof. Jean Chamberlain Chedjou**

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Version 1

# Name of the course

**Traffic modelling and simulation**

# ECTS credits

6 Credits, (**45 hours of Theory + 30 hours of Exercises & Lab**), 2nd semester

# Objectives

This lecture familiarizes students with the development of models corresponding to specific systems, scenarios, phenomena or events in transportation. The main focus is on road transportation, railway transportation, supply chain networks and logistics. For a given system, scenario, or phenomenon under investigation, mathematical models are obtained. Simulation algorithms (using MATLAB and SIMULINK) are further developed to solve the mathematical models obtained. The numerical solutions obtained are used to analyze the systems, scenarios and phenomena. This analysis helps to understand and control/optimize the complex dynamical behavior undergone by the systems, scenarios and phenomena at stake.

The Lecture also provide some basic knowledge of Neural Networks and the use of neural networks to analyze some selected systems, scenarios, and phenomena in transportation. Students also acquire some basic knowledge in optimization. The knowledge acquired is further used to solve some selected case studies related to the optimization of some scenarios at stake in the field of transportation (railway, road transportation, and supply chain networks, etc.).

This lecture also familiarizes students with mathematical modeling and simulation of various optimization problems selected in graph theory, road and railway traffic, and supply chain networks.

Overall, the main objectives of this lecture are expressed by the following keywords:  *modelling in transportation; simulation in transportation; neural networks, optimization over graph networks; optimization in road transportation; optimization in railway transportation; optimization in supply chain networks; scientific computing based on MATLAB.*

# Learning outcomes

The general expectation regarding the knowledge to be provided/acquired is as follows:

* Mastering of the basics concepts of systems’ modeling in transportation
* Mastering of the basics concepts of systems’ simulation in transportation
* Mastering of the traffic models presented by the literature and their use to analyze and understand the scenarios/events/phenomena described by the models.
* Mastering of the traffic simulation tools presented by the literature and their use to analyze and understand the scenarios/events/phenomena in transportation.
* Mastering the basic concepts of optimization and the application to some case studies
* Mastering the basic concepts of Neural Networks
* Learning how to model some specific scenarios in road transportation
* Learning how to model some specific scenarios in railway transportation
* Learning how to model some specific scenarios in supply chain networks
* Acquiring some basic knowledge in logistics and scheduling.
* Mastering the application of the concept of optimization in road transportation
* Mastering the application of the concept of optimization in railway transportation
* Mastering the application of the concept of optimization in supply chain networks
* Mastering the application of the concept of optimization in graph networks
* Acquiring some basic knowledge in computational engineering. Specifically, the use of MATLAB/SIMULINK for scientific computing (e.g. numerical simulation of nonlinear Ordinary Differential Equations (ODEs) and Partial Differential Equations (PDEs))

# Contents

1. **Introduction to traffic modeling, simulation, management and control**
   1. Some illustrative examples: *Road traffic, Rail traffic, Air traffic, Boat traffic, and Supply chain (traffic of Goods)*
   2. Definition of some important keywords and their illustration through concrete examples: Transportation, Traffic, modelling, model, Traffic theory, Simulation,
   3. Pros/Advantages and Cons/Drawbacks of modeling
   4. Pros/Advantages and Cons/Drawbacks of simulation
   5. Traffic stakeholders and traffic problems: Case 1. Road traffic; Case 2. Rail traffic.
   6. Approaches/methods for solving traffic problems
   7. Challenges of traffic modeling and simulation
   8. Traffic models classification: Static models; Dynamic models; Continuous model; Discrete model; Deterministic model; Stochastic model; Event-based model;
   9. Physical Interpretation of the modeling procedure: White-box modeling; Black-box modeling; Grey-box modeling.
   10. Presentation of traffic models: Macroscopic; Microscopic; Mesoscopic; Nanoscopic;
   11. Presentation of traffic simulation models/tools
   12. Cons/Advantages and Cons/Drawbacks of using traffic simulation models/tools
   13. Some illustrative examples of models corresponding to specific traffic scenarios: Macroscopic; Microscopic; Mesoscopic; Nanoscopic
2. **Overview of traffic models and traffic simulation tools**
   1. Models of specific road/rail traffic scenarios
      1. Microscopic; Macroscopic; Mesoscopic
   2. Three phase traffic theory
      1. Traffic states: *Free flow; Synchronized flow; Wide moving jam*
      2. Description and illustration of the aforementioned states in road traffic
      3. Description and illustration of the aforementioned states in rail traffic
   3. Some basic terminologies in road and/or rail traffic
      1. Cycle; Cycle length/time; Capacity; Congestion; Coordination; Delay; Density; Detection; Phase; Phase sequence; Split; Phase split; Approach; Actuation; Gap; Gap out; Level of service; Shockwave; Offset of traffic signals; Ramp metering; Pretimed controllers; actuated controllers; semi-actuated controllers; Fully-actuated controllers; Inductive loops; Camera-based controllers;
      2. Some concrete illustrative examples of the aforementioned terminologies in road and/or rail traffic.
   4. Description/presentation of some commonly used traffic simulation tools (commercial ones and open source ones)
      1. Simulation tools for macroscopic (road) traffic
      2. Simulation tools for microscopic (road) traffic
      3. Simulation tools for mesoscopic (road) traffic
      4. Simulation tools for supply chain networks
      5. Special tools for RAILWAY traffic simulation
3. Basics of neural networks and application in transportation
   1. Introduction to neural networks
      1. What is a neural network?
      2. Objectives and advantages of the use of neural networks
      3. History of artificial neural networks (ANNs)
      4. Some interesting applications of neural networks
   2. Neural networks structures
      1. How to build a neural network?
      2. How to construct artificial neurons?
      3. Model of biological neurons
      4. Functioning principle of biological neurons
      5. Functioning principle of artificial neural networks (ANNs)
      6. Difference between artificial and biological neural networks
   3. Learning/Training phase of artificial neural networks (ANNs)
      1. Description of some commonly used learning strategies/rules
      2. Illustrative examples of how the rules are used in/for specific applications
   4. Usage phase of artificial neural networks (ANNs)
      1. Illustration through case studies
      2. Comment on the convergence properties of ANNs
   5. Neuron model and network architecture
      1. Neuron model
         1. Single-input neuron
         2. Transfer functions
         3. Multiple input neuron
   6. Network architecture
      1. A layer of neurons
      2. Multiple layers of neurons
      3. Delay
      4. Integrator
      5. Recurrent networks
   7. Convergence of neural network architecture (or platform)
   8. Sample application examples of how to solve problems using neural networks
   9. Some exercises to check the knowledge acquired in the chapter
4. Basics of optimization and simulation algorithms/tools for optimization
   1. Linear programming (LP)
   2. Quadratic programming (QP)
   3. Case studies: Some illustrative application examples
   4. Neural networks for optimization
   5. Case studies: Some illustrative application examples
5. **Optimization in graph networks with applications in transportation**
   1. Mathematical modeling of the Shortest path problem (SPP) in graph networks with applications in transportation
   2. Mathematical modeling of the Minimum spanning tree (MST) in graph networks with applications in transportation
   3. Mathematical modeling of the Traveling Salesman Problem (TSP) in graph networks with applications in transportation. Extension to various Vehicle Routing Problem scenarios (VRP).
   4. Mathematical modeling of the Maximum Flow Problem (MFP) in graph networks with application examples in transportation
6. **Optimization in road transportation**
   1. Mathematical modeling of the traffic signal control principle at isolated (local) traffic junction: Traffic signals splitting, Green signal sharing, etc.
   2. Mathematical modeling of the traffic signal control principle in a network of coupled traffic junctions: Traffic signals splitting, Green signal sharing, etc.
7. **Optimization in railway transportation**
   1. Mathematical modelling of the train dynamics and optimization of the Energy consumption
   2. Mathematical modeling and optimization of the railway blocking problem
   3. Optimization of the train trajectory: Modelling concept and simulation algorithm/method
      1. Mathematical modelling in cases without delay
         1. Problem statement
         2. Effects of traffic lights/signals
         3. Signal response policy
         4. Green wave policy
      2. Mathematical modelling in cases of delays
         1. Problem statement
         2. Effects of traffic lights/signals
         3. Signal response policy
         4. Green wave policy
   4. Extension of the study in section 7.3 to the derivation of the “Optimization model” for two-train trajectory
   5. **Trains on time.** Optimization and Scheduling of railway time tables
      1. Minimization of transportation costs
      2. Minimization of procurement cost
      3. The Cyclic Railway Timetabling Problem (CRTP)
8. **Supply chain networks – Modelling and Analysis of the Dynamics of Supply Chain Networks**
   1. Overview of supply chain networks
   2. Modelling principle of supply chain networks
   3. Modelling and optimization of the assignment problem in a supply chain network
   4. Supply Chain Management Optimization Problem
9. **Scheduling – Fundamentals of Scheduling and Applications in Transportation**
   1. Overview of scheduling
   2. Principles of scheduling
   3. Modelling job-shop scheduling problems
   4. Railway scheduling by network optimization problem
   5. Modeling of the railway scheduling problem and time-tables optimization
   6. Modeling and optimization of the Crew scheduling problem in Railway transportation

# Teaching method

Lectures, case studies, Tutorials/exercises, Numerical coding using MATLAB.

* The slides are available for the whole lecture. These slides are must be provided to students (or must be uploaded in the MOODLE system). The full content of each slide is systematically explained by the Lecturer. Additional examples which are not included in slides will be proposed by the Lecturer to allow good understanding of the information provided.
* The slides contain exercises with solutions for the good understanding of the content of each chapter. These solutions are systematically explained (during the lecture) by the Lecturer.
* The Slides contain exercises without solutions to be solved by students during the lecture (this is part of oral exam). The students are fully assisted by the Lecturer in order to obtain correct/exact solutions to the proposed exercises. This will help to check whether the students have understood the chapters or not.
* Several exercises will be proposed by the Lecturer to be solved by students as projects. This will help to test the self-learning potential of students.
* Some MATLAB programming projects / Lab exercises as homeworks/assignments in groups

# Assessment method

Mid-term and final oral and/or written examination, exercises from case studies.

# Textbooks - Publications - Software

**Textbooks**

* Hagan M. T., Demuth H. B., Beale M. H., and Jesus O. De (2014). **Neural Network Design**, second edition, ISBN-13: 978-0971732117
* Treiber M., and Kesting A. (2013). **Traffic Flow Dynamics: Data, Models and Sim**ulation, Springer-Verlag, Berlin Heidelberg, ISBN 978-3-642-32460-4,
* Haight F. A., (2012). [**Mathematical Theories of Traffic Flow**, Academic Press,](https://www.amazon.com/Mathematical-Theories-Traffic-Frank-Haight/dp/0124110053/ref=sr_1_5?s=books&ie=UTF8&qid=1538662483&sr=1-5) ISBN-13: 978-0124110052
* Cascetta E. (2009). **Transportation Systems Analysis: Models and Applications**, Second Edition, Springer.
* Bondy J. A. and Murty U. S. R. (1982). Graph theory with applications, Fifth Edition, Elsevier Science Publishing Co.
* [Watson](http://www.worldcat.org/search?q=au%3AWatson%2C+Michael%2C&qt=hot_author) M.; [Lewis](http://www.worldcat.org/search?q=au%3ALewis%2C+Sara%2C&qt=hot_author) S.; [Cacioppi P.](http://www.worldcat.org/search?q=au%3ACacioppi+Peter%2C&qt=hot_author" \o "Search for more by this author) ; [Jayaraman](http://www.worldcat.org/search?q=au%3AJayaraman%2C+Jay%2C&qt=hot_author) J. (2014). **Supply chain network design : applying optimization and analytics to the global supply chain**, Second Edition, New Jersey Pearson Education.
* D. Davendra (2010). **Traveling Salesman Problem, Theory and Applications**, InTech, ISBN 978-953-307-426-9.

**Selected relevant Publications**

* Nagurney, A, A System-Optimization Perspective for Supply Chain Network Integration: The Horizontal Merger Case, Transportation Research E, vol. 45 (2009) 1-15.
* Peeters, L.W.P. (2003). Cyclic Railway Timetable Optimization, Erasmus Research Institute of Management (ERIM), Erasmus University Rotterdam.
* J. C. Chedjou and K. Kyamakya, Benchmarking a Recurrent Neural Network Based Efficient Shortest Path Problem (SPP) Solver Concept under Difficult Dynamic Parameter Settings Conditions, NeuroComputing, vol. 196 (2016) 175-209.
* J. C. Chedjou and K. Kyamakya, A Universal Concept Based on Cellular Neural Networks for Ultrafast and Flexible Solving of Differential Equations, IEEE Transactions on Neural Networks and Learning Systems, vol. 26, No. 4 (2015) 749-762.
* M. Larrañaga, J. Anselmi, U. Ayesta, P. Jacko, and A.Rom, Optimization Techniques Applied to Railway Systems( 2013) <hal-00780524>.
* C. Strotmann, Railway scheduling problems and their decomposition, Thesis/Dissertation (2007), University of Osnabrück, Germany.
* S. Göttlich, M. Herty, and A. Klars, Network Models for Supply Chains International Press, vol. 3, No. 4, (2005) 545–559.
* D. Huisman, L. G. Kroon, R. M. Lentink, and M. J.C.M. Vromans, Operations Research in Passenger Railway Transportation, Econometric Institute Netherlands (2005), Report EI2005-16

Software

**\*** Numerical Computing: Algorithmic/Coding and Model-Based Design

* **MATLAB TAH FULL SUITE** for scientific computing, MathWorks (1984), USA.

https://de.mathworks.com/academia/student\_version.html

* VISSIM (for microscopic simulation)
* VISUM (macroscopic simulation)
* MAS-T2erLab
* ITSUMO
* SUMO for road traffic simulation (at different levels): <http://www.sumo.dlr.de/userdoc/Sumo_at_a_Glance.html>
* SUMO for railway simulation: <http://www.sumo.dlr.de/userdoc/Simulation/Railways.html>
* PULSim: User-Based Adaptable Simulation Tool for Railway Planning and Operations