# TSL Dissertation Abstracts

# 2004 Transportation Science and Logistics Section Dissertation Prize Competition

Patrick Jaillet

Chair, 2004 TSL Dissertation Prize Competition

The Transportation Science and Logistics (TSL) Section Dissertation Prize Competition is the oldest and most prestigious competition for doctoral dissertations in the transportation science and logistics area. The 2004 TSL dissertation prize committee consisted of Professor Ravi Ahuja (University of Florida), Professor Amy Cohn (Michigan University), Professor Randy Hall (University of Southern California), Professor Mark Hickman (Arizona University), and Professor Patrick Jaillet (Massachusetts Institute of Technology).

Eligible doctoral dissertations were those completed and submitted between June 1, 2003, and May 31, 2004, in the general area of transportation science and logistics. To be considered, a dissertation had to be nominated by the thesis supervisor. This year we received 16 nominations. In addition to the large number of submissions, the quality of the theses was outstanding. I would like to extend my sincere thanks to the committee members for the time, effort, and professionalism they devoted to the difficult task of judging these entries. The awards were announced at the 2004 INFORMS Meeting in Denver.

It is important to remember that submissions to the TSL Dissertation Prize Competition are already distinguished by the fact that they have been nominated for the award. Each makes a unique and valuable contribution to transportation science and logistics, and all entrants and their advisors deserve warmest congratulations.

Abstracts for the 16 dissertations follow; winners are listed first and finalists' abstracts follow in alphabetical order by author.

**First Place**
Lawrence Snyder, Northwestern University
Advisor: Mark Daskin
"Supply Chain Robustness and Reliability: Models and Algorithms"

**Honorable Mention**
Miguel Figliozzi, University of Maryland
Advisors: Hani Mahmassani and Patrick Jaillet
"Performance and Analysis of Spot Truck-Load Procurement Markets Using Sequential Auctions"

**Finalists**
Jeffrey Michael Casello, University of Pennsylvania
Advisor: Vukan Vuchic
"Improving Regional Transportation System Performance Through Increased Suburban Intermodalism: A User Cost Modeling Approach"

Elaine J. Chang, Northwestern University
Advisor: Thanasis Ziliaskopoulos
"Time-Varying Intermodal Person Trip Assignment"

Chi-Nan Chin, University of Southern California
Advisor: Randolph Hall
"A Slot Model for a Highway Flow Optimization Through Entry, Exit, and Flow Control"

Frank Crittin, École Polytechnique Fédérale de Lausanne
Advisor: Michel Bierlaire
"New Algorithmic Methods for Real-Time Transportation Problems"

Laurie Garrow, Northwestern University
Advisor: Frank Koppelman
"Comparison of Choice Models Representing Correlation and Random Taste Variation: An Application to Airline Passengers' Rescheduling Behavior"

Paulo Goncalves, Massachusetts Institute of Technology
Advisor: John Sterman
"Demand Bubbles and Phantom Orders in Supply Chains"

Dennis Huisman, Erasmus University, Rotterdam
Advisors: Albert Wagelmans and Rommert Dekker
"Integrated and Dynamic Vehicle and Crew Scheduling"

Wenlong Jin, University of California, Davis
Advisor: Michael Zhang
"Kinematic Wave Models of Network Vehicular Traffic"

Laura Sumi Kang, Massachusetts Institute of Technology
Advisor: John-Paul Clarke
"Degradable Airline Scheduling and Approach to Improve Operational Robustness and Differentiate Service Quality"

Zongzhi Li, Purdue University
Advisor: Kumares C. Sinha
"Multicriteria a Highway Programming Incorporating Risk and Uncertainty: A Methodology for Highway Asset Management System"

Steven Logghe, Catholic University, Louvain
Advisor: L. H. Immers
"Dynamic Modeling of Heterogeneous Vehicular Traffic"

Leon Peeters, Erasmus University, Rotterdam
Advisor: Leo Kroon
"Cyclic Railway Timetable Optimization"

Nicolas E. Stier-Moses, Massachusetts Institute of Technology
Advisor: Andreas Schultz
"Selfish Versus Coordinated Routing in Network Games"

Weihua Xiao, Rutgers University
Advisor: Melike Baykal-Gürsoy and Kaan Ozbay
"Modeling, Evaluation, and Optimization of Traffic Incident Management Systems"

# Supply Chain Robustness and Reliability: Models and Algorithms

Lawrence Snyder

Northwestern University

Mark Daskin (Advisor)

Supply chain design models have traditionally treated the world as if we knew everything about it with certainty. In reality, however, parameter estimates may be inaccurate due to poor forecasts, measurement errors, changing demand patterns, or other factors. Moreover, even if all of the parameters of the supply chain are known with certainty, the system may face disruptions from time to time, for example, due to inclement weather, labor actions, or sabotage. This dissertation studies models for designing supply chains that are *robust* (i.e., perform well with respect to uncertainties in the data, such as demand) and *reliable* (i.e., perform well when parts of the system fail).

The first half of this dissertation is concerned with models for robust supply chain design. The first of these models minimizes the expected systemwide cost, including costs for facility location, transportation, and inventory. The second model adds a constraint that restricts the regret in any scenario to be within a prespecified limit. Both models are solved using Lagrangian relaxation. The second model presents an additional challenge because feasible solutions cannot always be found easily, and it may even be difficult to determine whether a given instance is feasible. We present strategies for overcoming these difficulties. We also formulate and solve regret-constrained and minimax-regret versions of two classical facility location problems.

In the second half of the dissertation, we present a new approach to supply chain design that attempts to choose facility locations so that if a distribution center becomes unavailable, the resulting cost of operating the system (called the "failure cost") is not excessive. We discuss two types of reliability models, one that considers the maximum failure cost and one that considers the expected failure cost. We propose exact and heuristic solution methods for these problems. Computational results from both models demonstrate empirically that large improvements in reliability are often possible with small increases in cost.

# Performance and Analysis of Spot Truck-Load Procurement Markets Using Sequential Auctions

Miguel Figliozzi

University of Maryland

Hani Mahmassani and Patrick Jaillet (Advisors)

Information and communication technologies are transforming key market processes and the very architecture of the markets. The Internet and especially auctions have emerged as an effective catalyst to doing business in electronic marketplaces. The effect and impact of these changes on the logistics and freight transportation sector are unraveling as well as challenging researchers, academics, and practitioners.

One salient characteristic of this dissertation is the use of sequential auctions to model an ongoing transportation market. As a result, the problem studied is characterized not only as strategically competi-

tive, but also as essentially dynamic. This dissertation focuses on carriers' competition in a spot truck-load procurement market (TLPM) using sequential auctions. Competition in this transportation marketplace is studied under different supply/demand conditions, auction formats, and carriers' behavioral assumptions. Carrier participation in a TLPM requires the ongoing implementation of decisions regarding two distinct problems: the profit maximization problem (choosing the best bid) and the fleet management problem (assigning the best fleet to serve the acquired shipments).

The original contributions to this dissertation stem from the study of carriers' decision-making processes and fleet management strategies in a competitive environment. Given the intractability of the proposed TLPM sequential auction decision problems, carriers are assumed to be bounded rationally. A framework to study carriers' behavior in a TLPM is presented. In this framework carriers' decision-making processes and rationality assumptions are analyzed. Components of this behavioral framework include fleet management technology, carriers' level of rationality, auction format, and market settings.

This dissertation also places a unique emphasis on studying the effects of fleet management asymmetries on a competitive marketplace. As such, a methodology to compare dynamic fleet management technologies is developed. Fleet management technologies are also studied under a particular set of bounded rationality assumptions and bidding learning mechanisms. These learning mechanisms include reinforcement learning and fictitious play. The performance of different auction settings is also studied. Simulated scenarios are presented and their results are discussed.

# Improving Regional Transportation System Performance Through Increased Suburban Intermodalism: User Cost Modeling Approach

Jeffrey Michael Casello
*University of Pennsylvania*

Vukan Vuchic (Advisor)

This research presents a combination of economics, spatial analysis, and transportation modeling to analyze the effects of increased intermodalism on transportation system performance. Using utility theory to model traveler behavior, a conceptual cost model is developed to explore how auto pricing and transit service quality affect mode choice. The results suggest that increasing the disutility of automobile travel while providing high-quality transit reduces total system and average user costs at a sustainable user equilibrium.

To test the validity of these conceptual findings in a larger transportation network, a multimodal traffic assignment model is developed and solved for Philadelphia, Pennsylvania. The model's trip table includes trips ends for which transit competes effectively with private automobiles—in areas with high-density land uses. Urban researchers call these locations "activity centers" and define them based on employment levels. This research extends the definition to include the trip-generating characteristics of a center's employment types.

The network representation includes freeway and arterial links connecting activity centers. Transit modes are represented by artificial links with fixed travel times equal to the scheduled travel time (including transfers), and an out of pocket expense equal to the transit fare. The origin-based algorithm is used to solve the traffic assignment problem to a user equilibrium condition. Pertinent measures of effectiveness include transit modal split, total system delay (network congestion), and a transit "competitiveness" measure defined for individual and aggregated trip ends.

Three auto disincentives measures are tested individually with limited improvement in system performance. Similarly, three transit incentives are evaluated; only modest gains in system performance are

observed. Finally, combinations of auto disincentives and transit incentives are implemented. The combined measures markedly improve system perfor- mance and reduce user costs compared to the measures tested independently, thereby validating the conceptual findings on a subregional level.

# Time-Varying Intermodal Person Trip Assignment

Elaine J. Chang
Northwestern University

Thanasis Ziliaskopoulos (Advisor)

This dissertation focuses on the incorporation of buses into both system-optimal and user equilibrium. Dynamic traffic assignment models are explored. Specifically, a cell transmission-based, single-destination, system-optimal integer linear programming model of intermodal trips on a network of cars and buses is presented, and the model is solved on a test network using standard mathematical programming methods. Also, the intermodal user equilibrium problem is formulated as a variational inequality, and an inner approximation solution algorithm that minimizes an equilibrium gap function is presented. Algorithm convergence is proven for cases with continuous, monotonic cost functions, and heuristic variations are proposed for problems where these assumptions do not hold. While the inner approximation assignment algorithm may be applied with any traffic propagation model for calculation of link costs, the approach implemented in the disser- tation is a cell transmission-based simulation model. Further, for path generation, a label-correcting inter- modal least cost path algorithm, which accounts for both time varying and fixed travel and transfer costs, is presented with proofs of convergence and correct- ness.

Computational results are presented for the inner approximation DTA model first on a single-mode automobile test network, and then on a large-scale multimodal network of cars and buses. This multi- modal automobile assignment-based approach is used in a real-world evaluation of the regional impacts of transit signal priority (TSP). Key findings relate not only to the impacts of TSP, but also to the practi- cal aspects of realistic regional simulation, such as challenges in data acquisition and model validation. In addition, computational results are presented to explore the behavior of the inner assignment algo- rithm for the intermodal problem.

# A Slot Model for Highway Flow Optimization Through Entry, Exit, and Flow Control

Chi-Nan Chin
University of Southern California

Randolph Hall (Advisor)

The objective of this thesis is to optimize per- formance of automated highway systems (AHS) through management of space accounting for interac- tion between entrance and exit processes. To accom- plish this objective, we develop a comprehensive framework (including a new integrated highway model called the moving slot model) and operational strategies (called slot/lane assignment rules). The

model manages highway space to maximize capacity accounting for safety and vehicle maneuvers. Slot assignment rules sort vehicles into specific patterns of destinations through entry and lane-change control such that vehicles can exit successfully and require the minimal ramp space for exiting. Lane/slot assignment rules regulate traffic flow among lanes and specify lane-change positions such that the highway throughput is maximized and the number of lane changes is minimized. This research also aims to expedite the application of AHS without significantly altering current highway configurations, while optimizing performance in terms of throughput and travel time.

In the moving slot model, an operational unit (called a slot in a one-lane highway and a stack in a multilane highway), contains the minimal space for accommodating vehicles and supporting safe maneuvers. Hence, a maneuver in one unit will not affect that in another units'. This design provides independence among operational units and reduces the complexity of system control. The model is adapted to various system requirements by reserving necessary space in an operational unit. This research provides an efficient and effective design for the operation of highway systems, especially under heavy traffic conditions. We provide both theoretical and simulation results for the system performance of a simplified highway operating under the proposed framework. Simulations are used to verify proposed operational rules and to derive the performance of the framework applied on practical highway configurations. In general, we can achieve a double capacity of conventional highways (i.e., 4,000 vehicles per hour, per lane or more).

# New Algorithmic Methods for Real-Time Transportation Problems

## Frank Crittin

École Polytechnique Fédérale de Lausanne

Michel Bierlaire (Advisor)

The use of more and more complex simulation tools on high-performance computers requires solving instances of least-squares problems, systems of nonlinear equations, and fixed point problems arising in many transportation contexts. The main thrust of this thesis is the design of new algorithmic methods for solving large-scale instances of these problems. Although they are relevant in many different applications, we concentrate specifically on real applications encountered in the context of intelligent transportation systems to illustrate their performances.

First, we propose a new approach for the estimation and prediction of origin-destination tables. This problem is usually solved using a Kalman filter approach, which refers to both formulation and solution algorithms. We prefer to consider an explicit least-squates formulation. It offers convenient and flexible algorithms especially designed to solve large-scale problems. Numerical results provide evidence that this approach requires significantly less computation effort than the Kalman filter algorithm. Moreover, it allows us to consider larger problems, likely to occur in real applications.

Second, the consistent anticipatory route guidance (CARG) problem is generally formulated as a fixed point problem. In this dissertation we have reformulated the CARG problem as the resolution of a system of nonlinear equations. A new class of iterative methods has been introduced. The main idea is to generalize classical secant methods by building the secant method using more than two iterates. We derive from this class of methods a metric-free algorithm designed to solve large-scale systems of nonlinear equations. Numerical results on the CRAG problem emphasize the excellent behavior of this method in a real-time context to classical fixed point methods.

# Comparison of Choice Models Representing Correlation and Random Taste Variation: An Application to Airline Passengers' Rescheduling Behavior

Laurie Garrow
Northwestern University

Frank Koppelman (Advisor)

There has been increasing interest in using mixed multinomial logit models to study choice behavior because they enable random taste variation by allowing parameters of the utility function to vary across individuals and have been shown to theoretically approximate any random utility model via the inclusion of an appropriate set of error components. However, this study provides a motivation for integrating complex closed-form models to represent correlation among alternatives with random coefficients. Using the nested logit (NL) model as an example, we demonstrate that while a mixed model can approximate an NL model theoretically, empirically the mixture analog may be a poor approximation in important contexts. Further, we show that important information used to interpret the implications of model results, namely correlation among alternatives, is not always identified in mixture models.

A second theoretical contribution of this work relates to efficient estimation of NL models for choice-based samples. Currently, the benefit of collecting choice-based samples diminishes when modeling consumers' behavior using NL models because of the need to use consistent estimators that are often inefficient and/or complicated to implement. In contrast, benefits are retained when using the simple multinomial logit model because, under conditions relatively easy to satisfy in practice, the exogenous sample maximum likelihood (ESML) estimator can be used. This study shows the ESML estimator can also be used with choice-based samples for NL models.

Finally, this work contributes to the state of the art and practice in airline yield management. This work represents the most comprehensive study of airline passengers' day of departure rescheduling behavior and is the first to examine standby behavior. It demonstrates how the failure to distinguish between standby and no-show behavior may lead to costly errors in yield management. A validation analysis demonstrates the benefits of incorporating passenger data and outbound/inbound itinerary information in airline no-show models.

# Demand Bubbles and Phantom Orders in Supply Chains

Paulo Goncalves
Massachusetts Institute of Technology

John Sterman (Advisor)

Though often analyzed separately, supply chain instability and customer demand interact through product availability. This dissertation explores two aspects of supply chain instability that are influenced by customers' response to shortages: "phantom," or inflated orders, and lost sales. The former takes place when the supplier provides a crucial product to the customer, with few alternative options for timely replacement. The latter takes place when the supplier provides a product with close substitutes available

in the market. Through three papers, one addressing lost sales and two phantom orders, the research investigates the impact of customer responses to supply chain instability. The first paper underscores the costs of lean inventory strategies for a semiconductor manufacturer operating a hybrid push-pull production system. It finds that inventory buffers are more valuable than previous models suggest and that demand instability can cause supply chains to shift the mode of operation leading to diminished performance. This is due to the realization that supply chain instability models that assume exogenous demand underestimate the amplification in the chain and the value of inventory buffers.

The second paper develops a theoretical model of the phenomenon of order amplification due to shortages leading to demand bubbles. It describes the structures and decision rules that contribute to bubbles and suggests policies for improvement. For instance, while companies may have access to real-time information on supply availability and delivery delays, it is destabilizing to share such information with customers in a context of fierce competition and scarce supply.

The last paper investigates an actual demand bubble in the agribusiness industry, where hoarding took place during shortages of "hot" products. Dealer hoarding generated large amounts of seeds returned to the supplier. Several supplier actions actually intensified hoarding behavior, worsening the problem. The analysis suggests several policies that effectively reduced the volume of returns.

# Integrated and Dynamic Vehicle and Crew Scheduling

## Dennis Huisman
### Erasmus University, Rotterdam

### Albert Wagelmans and Rommert Dekker (Advisors)

Due to increased competition in the public transport market and the pressure on governments to cut expenses, increasing attention has been paid to cost reductions in public transportation. Because the main resources used in public transportation are vehicles and crews, producing efficient vehicle and crew schedules is an important issue.

A sequential approach, i.e., vehicle scheduling followed by crew scheduling, does not guarantee an overall optimal solution. Therefore, integrated approaches are considered in this thesis. For different cases, mathematical models are presented and several algorithms are developed to solve these models. Computational tests demonstrate the quality of these algorithms.

In addition to cost reductions, the reliability of the public transport services for the passengers is an important issue. The disadvantage of the traditional, static planning approach is that, when a delay occurs, the next trip performed by that vehicle and/or driver will often start late. Therefore, new delays can occur that may have a similar "snowball" effect. A dynamic planning approach has been developed to prevent such an effect.

# Kinematic Wave Models of Network Vehicular Traffic

## Wenlong Jin
### University of California, Davis

### Michael Zhang (Advisor)

The kinematic wave theory has been a good candidate for studying vehicular traffic. In this dissertation, we study kinematic wave models of network traffic, which are expected to be theoretically rigorous, numerically reliable, and computationally efficient.

For inhomogeneous links, we reformulate the Lighthill-Whitham-Richards model into a nonlinear resonant system. In addition to shock and rarefaction waves, standing (transition) waves appear in the 10 basic wave solutions. The solutions are consistent with those by the supply-demand method.

For merging traffic, we examine existing supply-demand models and, particularly, distribution schemes. Further, we propose a new distribution

scheme, which captures key merging characteristics and leads to a model that is computationally efficient and easy to calibrate.

For diverging traffic, we propose an instantaneous kinematic wave model, consisting of nonlinear resonant systems. After studying the seven basic wave solutions, we show that this model is equivalent to a supply-demand model with modified definitions of traffic demands.

For traffic with mixed-type vehicles, we show the existence of contact waves. Using simulations from the Godunov method, we demonstrate that the first-in-first-out (FIFO) principle is observed in this model.

For network traffic flow, we propose a multi-commodity kinematic wave (MCKW) model, in which we combine kinematic wave models of different network components and a commodity-based kinematic wave theory. We also propose an implementation of the MCKW simulation and carefully design the data structure for network topology, traffic characteristics, and simulation algorithms. The solutions are consistent with FIFO principle in the order of a time interval.

For a road network with a single origin-destination pair and two routes, we first demonstrate the formation of an equilibrium state and find multiple equilibrium status for different route distributions. We then show the formation of periodic oscillations and discuss their structure and properties.

Finally, we summarize our work and discuss future research directions.

# Degradable Airline Scheduling and Approach to Improve Operational Robustness and Differentiate Service Quality

## Laura Sumi Kang
### Massachusetts Institute of Technology

John-Paul Clarke (Advisor)

We present a methodology for deriving robust airline schedules that are not vulnerable to disruptions caused by bad weather. In this methodology, the existing schedule is partitioned into independent subschedules or layers—prioritized on the basis of revenue—that provide airlines with a clear delay/cancellation policy and may enable them to market and sell tickets for flight legs based on passenger preference for reliability.

We present three different ways to incorporate degradability into the scheduling process: (1) between flight scheduling and fleet assignment (degradable schedule partitioning model), (2) with fleet assignment (degradable fleet assignment model), and (3) with aircraft routing (degradable aircraft routing model). Each problem is modeled as an integer program. Search algorithms are applied to the degradable aircraft routing model, which has a large number of decision variables.

Results indicate that we can successfully assign flight legs with high-revenue itineraries in the higher priority layer without adding aircraft or changing the schedule, and differentiate the service quality for passengers in different priority layers. Passengers in the high-priority layers have much less delay and fewer cancellations than passengers in low-priority layers, even during bad weather. In terms of recovery cost (which includes revenue lost operational cost saving, and crew delay cost) degradable airline schedules can save up to $30,000 per day. Degradable airline schedules have a cost-savings effect, especially when an airport with a high-capacity reduction in bad weather is affected by bad weather.

# Multicriteria Highway Programming Incorporating Risk and Uncertainty: A Methodology for a Highway Asset Management System

Zongzhi Li

Purdue University

Kumares C. Sinha (Advisor)

Highway asset management is a systematic process that aims to preserve, expand, and operate highway assets in the most cost-effective manner. This dissertation proposed a methodology for the development of a highway asset management system that addressed issues of asset valuation, performance modeling, marginal benefit analysis, and multicriteria decision making, including trade-off analysis, and project selection and programming. While most existing management systems deal with individual physical highway assets (pavements, bridges, etc.) or system usage (highway safety, congestion, etc.) under certainty or risk only, this research also focused on the management of an entire highway network that incorporated trade-off decisions involving uncertainty.

First, a set of system goals, asset management programs, and performance indicators associated with various programs were classified. Network-level highway user cost was computed. Statistical models were then calibrated for pavements, bridges, and network-level user cost, using data related to state highways in Indiana. To facilitate trade-off analysis, the relative weights of system goals and performance indicators under each goal, and systemwide utility functions

and standardized focus, gain-over-loss ratio functions were established based on utility theory and Shackle's model, respectively. This was done for different asset management programs for trade-offs under certainty, risk, and uncertainty using data collected through a series of questionnaire surveys.

Finally, a system optimization model, along with a solution algorithm using Lagrangian relaxation techniques, was formulated on the basis of the multichoice multidimensional knapsack problem to facilitate project selection and programming. A highway asset management system software program was developed and utilized in a case study for systemwide project selection using information on candidate projects proposed for state highway programming in Indiana during 1998–2001.

For all given years and regardless of the trade-off decision under certainty, risk, or uncertainty, the software outputs matched with the results of actual highway programming at least 85% of the time. The case study results validated the proposed methodology and research findings and also revealed the advantages of using such an automated system for overall highway asset management practice.

# Dynamic Modeling of Heterogeneous Vehicular Traffic

Steven Logghe

Catholic University, Louvain

L. H. Immers (Advisor)

In the original macroscopic traffic flow model the traffic on a motorway is idealized to a homogeneous fluidum. In this model the vehicles and their drivers are represented by identical fluid particles in a tube.

This dissertation takes into account the heterogeneous properties of traffic. To this end, the traffic flow is subdivided into homogeneous classes. Each

class consists of vehicles and drivers that share the same characteristics. Modeling heterogeneous traffic, in this case, comprises the description of homogeneous classes and the interactions between the different classes.

For each road section, a class is characterized by its maximum speed, its vehicle length, and its capacity. The capacity pertaining to a class signifies the maxi-

mum traffic intensity that prevails when vehicles from that specific class have exclusive use of the road.

The interactions between the different classes are based on the user optimum: it is assumed that each driver maximizes his own speed and that fast vehicles are unable to affect the speed of slow vehicles. Slower vehicles, in this view, behave like moving bottlenecks.

The heterogeneous model presented in this dissertation comprises a mathematical formulation that can be solved analytically and graphically. In addition, a numerical scheme has been constructed. This enables a computer implementation of the model, allowing for a rapid computation of approximating solutions.

The developed model has been extended for use on complete transport networks. A case-study application of the model illustrates its practical usefulness. The dissertation concludes with a critical review of the assumptions and properties pertaining to the model, and a brief mention of possible model extensions.

# Cyclic Railway Timetable Optimization

## Leon Peeters
Erasmus University, Rotterdam

Leo Kroon (Advisor)

This thesis describes mathematical models and solution methods for constructing high-quality cyclic railway timetables. In a cyclic timetable, a train for a certain destination leaves a certain station at the same time every cycle time (say every half an hour, every hour, or every two hours).

Cyclic timetables are widely used in European national railways, and in urban rail, metro, and bus transport systems. A cyclic timetable offers a clear and transparent product to railway customers, who only need to memorize the minutes of the hour at which their regular trains depart. Because of the important role of timetable planning for railway operators and railway infrastructure managers, timetabling models and methods for optimizing cyclic railway timetables provide a valuable tool for these organizations.

The thesis presents a mathematical model for optimizing cyclic railway timetables. Various objectives are considered: minimizing passenger travel times, maximizing timetable robustness, minimizing the cost of the required rolling stock, and minimizing the constraint violation for infeasible instances. The model takes all important practical requirements into account, such as trip times, dwell times, connections between trains, synchronization of trains, etc.

This thesis thoroughly investigates the theoretical foundations of the model, which include cyclic sequencing, periodic tensions, cycles in graphs, and cycle bases of graphs. It describes algorithms for constructing good cycle bases, cutting planes for the model, and an iterative integer variable fixation heuristic. The developed model, theory, and algorithms are tested on various real-life cyclic railway timetabling instances. The thesis further presents several extensions of the basic model, such as variable train trip times and the associated safety requirements, and flexible connections between groups of trains.

# Selfish Versus Coordinated Routing in Network Games

## Nicolas E. Stier-Moses
Massachusetts Institute of Technology

Sndreas Schultz (Advisor)

It is widely hoped that intelligent transportation systems can help to alleviate the problem of ever-increasing traffic congestion. Among the proposed systems that have emerged in the last decade, so-called route guidance devices are an especially promising technology. We propose a novel approach to route guidance that aims at a traffic assignment that minimizes the total travel time in the network, subject to certain user constraints. When deciding on recommendations for users, we do not consider routes that are too long because users are not likely to follow them. Our approach offers significant advan-

tages over both the traditionally considered user equilibrium and the system optimum. For several real-world instances, we compute traffic assignments of notably smaller total latency than in equilibrium, yet of similar fairness. Furthermore, we provide theoretical results that explain the conclusions derived from the computational study.

Motivated by the analysis of the efficiency of the proposed system, we also compare user equilibria to system optima because the cost of the solutions provided by the route-guidance system is between that of these two traffic patterns. It has actually been a long-standing open question to analyze this gap. We contribute to an answer by showing that in networks with side constraints and very general link performance functions, users' independent and selfish decisions inadvertently drive the solution toward optimality. In addition, we extend the analysis to other objective functions commonly found in applications. This connection to individual decision making proves fruitful; not only does it provide us with insights and additional understanding of the problems we study, but it also allows us to design approximation algorithms for hard computational problems.

# Modeling, Evaluation, and Optimization of Traffic Incident Management Systems

Weihua Xiao
Rutgers University

Melike Baykal-Gürsoy and Kaan Ozbay (Advisors)

It is now widely accepted that the congestion and congestion-related problems can be decreased by the proper use of an efficient incident management system (IMS). Because the initial investment, maintenance cost, and operating cost of each response unit is considerable, there is a great need for reliable models to help evaluate and optimize the performance of such systems.

In the performance analysis area, a steady-state $M/M/C$ queueing system under batch service interruptions is introduced to model the traffic flow on a roadway link, subject to incidents. We analyze this system in steady state and present a scheme to obtain the generating function of stationary number of vehicles on a link. For those links with large $C$ values, $M/M/\infty$ queues under batch service interruptions can be used as an approximation. We investigate an $M/M/\infty$ queueing system subject to random interruptions of exponentially distributed durations. It is shown that the number of customers present in the system in equilibrium is the sum of two independent random variables. One of these is the number of customers present in an ordinary $M/M/\infty$ queue without interruptions.

For incident response and resource allocation problems in traffic incident management, we propose mathematical programming models with probabilistic constraints to address the uncertain conditions in an IMS. A mixed-integer programming model with probabilistic constraints is proposed to address the dispatching problem with consideration given to the stochastic resource requirements at the sites of the potential incidents. For the resource allocation problem, assuming that the stochastic distribution of incidents over a network is given, we introduce a mathematical model to determine the number of service vehicles allocated to each depot to meet the requirements of the potential incidents by taking into account the stochastic nature of the resource requirement and incident occurrence probabilities.

We also develop a computer simulation software package with $C++$ programming language to evaluate the performance of IMS. This simulation software can be used to simulate the occurrence of highway incidents, the dispatching of emergency vehicles, and the free service patrol on the network. Using this simulation software, we investigate IMS in the southern New Jersey highway network. The investigation results could provide valuable information to the decision makers on how to improve the system performance.