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TSS Dissertation Abstracts

Abstracts for the 1992 Transportation Science Section Dissertation Prize Competition

ANNA NAGURNEY

Chair, 1992 TSS Dissertation Prize Competition

Nine dissertations were submitted to the 1992 Transportation Science Section dissertation prize competition. The judges were:

- Professor Dimitris Bertsimas, Massachusetts Institute of Technology;
- Professor Moshe Dror, University of Arizona at Tucson;
- Professor Hani S. Mahmassani, University of Texas at Austin;
- Professor Patrice Marcotte, College Militaire Royal de Saint Jean, and Centre de Recherche sur les Transports, Canada;
- Professor Jeff McGill, University of Denver;

with Professor Anna Nagurney of the University of Massachusetts at Amherst serving as Chair of the committee.

The judges were asked by the chair to read and evaluate all dissertations, except those from their home institutions. This year's submissions revealed the breadth and intellectual depth of research activity in transportation science.

The first prize was awarded to Dr. JULIEN BRAMEL for his dissertation, "Analytical Results and Algorithms for Vehicle Routing Problems with Bin-Packing Features." The committee awarded an honorable mention to Dr. PETER B. VRANAS for his dissertation, "The Multi-Airport Ground-Holding Problem in Air Traffic Control," and a letter of commendation to Dr. MUSTAFA C. PINAR for his dissertation, "Decomposition and Parallel Solution of Network-Structured Optimization Problems." The awards were formally announced at the Transportation Science Section meeting at the ORSA/TIMS Fall Meeting in San Francisco on the evening of November 2, 1992.

On behalf of the dissertation prize committee and the transportation science community, I congratulate the winners and all other applicants, as well as their dissertation supervisors, and thank them for their participation in this year's competition.

I wish to also extend my gratitude to all the judges for the time and care they devoted to this professional service.

The abstracts of the nine theses submitted to the competition are given below.

Analytical Results and Algorithms for Vehicle Routing Problems with Bin-Packing Features

JULIEN BRAMEL

Due to the increased importance of the service sector of the economy, there is a need for a better analytical understanding of service and distribution systems. In addition, there is a demand for practical algorithms that solve integrated distribution problems involving inventory issues, vehicle capacity constraints, and time constraints. Identifying the important cost components of the distribution system and how to best adapt distribution strategies to minimize these costs are the main topics of this dissertation. In five chapters, we analyze models that integrate inventory and transportation costs as well as models involving time constraints. We develop practical algorithms to provide good policies, as well as providing accurate lower bounds to assess the quality of these solutions.

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One of the combinatorial problems at the core of most of these distribution systems is the Capacitated Vehicle Routing Problem (CVRP) which can be described as follows: A set of geographically dispersed customers must be served by vehicles of limited capacity initially located at a given depot. Associated with each customer is a non-negative demand which represents the amount of load that must be delivered to that customer. The objective is to design efficient routes for the vehicles such that each customer receives its demand, the total load delivered by a vehicle does not exceed its capacity and the total distance traveled is as small as possible.

In the first chapter, we study the CVRP. Since the vehicle capacity is the most binding constraint, the analysis entails a thorough understanding of the bin-packing problem. In this problem, a set of items of different sizes must be packed into equal size bins in such a way that the number of bins used is as small as possible. It is one of the most well studied problems in combinatorial mathematics. If we view the vehicles as bins, and the customer demands as item sizes, the problem is exactly a bin-packing problem with a more complex cost structure. In this chapter, we focus on the average-case performance of heuristics for the CVRP. If a customer's demand is allowed to be split between two or more vehicles, then the bin-packing problem becomes trivial, so we concentrate on the harder case where only one vehicle can serve a customer. As HAIMOVICH and RINNOOY KAN (*Math. of OR*, 1985) pointed out "... *this additional constraint introduces bin-packing features into the routing problem and an appropriate solution method is not easily found.*" Using a simple region partitioning heuristic, we show that asymptotically the CVRP with unsplit demands is no more difficult than the corresponding bin-packing problem. We derive new algorithms for the CVRP, based on asymptotically optimal bin-packing heuristics, and show that these heuristics are also optimal for the CVRP.

Due to the practical importance of the CVRP, many heuristics have been suggested and empirically analyzed in the last three decades. This includes the class of heuristics called two-phase methods. These heuristics are of one of two types: (i) cluster first-route second, or (ii) route first-cluster second. In the next chapter we focus our attention on the latter class which includes the Optimal Partitioning heuristic (BEASLEY (1983)) and the Sweep algorithm (GILLET and MILLER (1974)). We prove that these classical heuristics are in fact *asymptotically nonoptimal*. They all have an inherent flaw: not enough effort is spent trying to reduce the bin-packing component of the cost. For instance, the solution produced by the Optimal Partitioning heuristic, which is the best available heuristic for the CVRP in terms of worst-case performance, approaches a value which is 33% above the minimal cost for a simple special case. The Sweep algorithm tends to be even worse. Hence, as a result of this analysis; on the one hand, we show that traditional algorithms are probably bad for large problems, on the other hand, we can actually know for what types of problems each heuristic is better suited.

In the next chapter, we focus on practical algorithms for the CVRP and other routing problems, such as the Inventory-Routing Problem (IRP). Based on the insights gained from Chapters 2 and 3, we develop a general framework for solving these problems. This solution method, which we prove is asymptotically optimal in the case of the CVRP, involves the formulation of the routing problem as a traditional location model commonly called the Capacitated Concentrator Location Problem (CCLP). The general heuristic we develop consists of modeling the routing problem as an instance of the CCLP, then solving the CCLP, using Lagrangian relaxation, a subgradient procedure and a branch and bound algorithm. The solution produced is then transformed back into a solution to the original routing problem.

Due to the general nature of the formulation, many variations of the heuristic are possible. We have used different versions to solve the benchmark problems for the CVRP in the literature, and have had much success. In fact, out of 9 problems, the general heuristic provides a solution better than the best known solution in 4 of them. We also apply the techniques to the IRP, also called the One Warehouse Multi-Retailer Distribution Problem. In this problem, a set of n retailers are geographically distributed in a service region. The retailers experience a fixed deterministic demand rate for the items. Vehicles are kept at a central warehouse where it is assumed an unlimited supply of items is available. The problem is to plan a schedule for the replenishment of each of the retailers' inventories, and to design efficient routes to deliver the items subject to the vehicle capacity constraint. The objective is to minimize long run average inventory holding cost at the retailers plus transportation cost. Again, this inventory-routing problem is formulated as an instance of the CCLP, and then the CCLP is solved. The solution is transformed back into a feasible solution to the IRP. We develop a lower bound to assess the quality of the replenishment strategy, and show that the general heuristic just described performs well.

In the next chapter, we study the Vehicle Routing Problem with Time Windows. A set of geographically dispersed customers must be serviced by a set of vehicles initially located at a given depot. Associated with each customer is a service time. The working day is divided into equal length time windows, and each customer chooses independently in which time window service is required. We show that the problem can be solved using similar techniques to the CVRP. In other words, for special cases of service time distributions, we derive asymptotically optimal heuristics based on region partitioning schemes. This problem has obvious applications in the areas of telephone and cable television servicing.

In the last chapter, we study a different cost structure for the bin-packing problem. We consider the problem when the cost of a bin is a concave function of the number of items in the bin. Note that the classical bin-packing problem is a special case of this problem. As we demonstrate, this cost structure occurs in several partitioning problems. We derive worst-case results for well known heuristics developed for the classical bin-packing problem. As a result of this analysis, we also derive some new worst-case results for the classical bin-packing problem.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Graduate School of Arts and Sciences at Columbia University. The thesis advisor was Professor David Simchi-Levi.

The Multi-Airport Ground-Holding Problem in Air Traffic Control

PETER B. VRANAS

Congestion problems are becoming increasingly acute in major American and European airports. In 1990, for instance, the U.S. airline industry incurred losses of about $2.5 billion, while its direct delay costs due to congestion were of the order of $2 billion! The problem is expected to get worse, because demand for airport use is increasing, while airport capacity is stagnating.

A promising solution appears to be the imposition of group holds: delaying the departures of aircraft by not allowing them to start their engines and leave their gates even if they are ready to take off. Ground-holding policies make sense in the following situation. If an aircraft departs on time, it encounters congestion and incurs an airborne delay upon arrival at its destination; but if its departure is delayed, the aircraft arrives at its destination at a later time when no congestion is present and no airborne delay is incurred. Therefore, the objective of the ground-holding policies is to absorb airborne delays on the ground. This can reduce significantly the total delay costs because airborne delays are much costlier than ground delays, mainly due to fuel costs.

This thesis investigates the Ground-Holding Problem (GHP), defined as the problem of allocating ground holds which minimize the total (ground plus airborne) delay cost for all flights in a general network of airports. Previous research on the GHP has been restricted to the single-airport case, neglecting thus "network effects" resulting from the propagation of delays between successive flights scheduled to be performed by the same aircraft.

In this thesis the *multi*-airport GHP is dealt with for the first time. Both static and dynamic versions of the problem are examined. Several pure 0-1 integer programming formulations are given. These formulations capture the essential aspects of the problem while being remarkably simple, and are sufficiently flexible to accommodate various degrees of modeling detail. For instance, the formulations enable one to impose airborne delays by means of *en route* speed reductions, to cancel flights, and to have interdependent departure and arrival capacities by controlling runway use.

The compactness of the formulation makes large-scale GHPs tractable: numerical results, achieved in reasonable computation times, are presented for networks with as many as 6 airports and 3000 flights. The behavior of the problem for various combinations of the input parameters is extensively investigated. It is found that solving single-airport GHPs for the individual airports results in highly infeasible solutions for the network problem. It is also found that optimal multi-airport ground holds can result in significant cost savings compared to heuristics approximating, to some extent, current ground-holding practice.

In conclusion: (1) The fundamental contribution of the thesis is an efficient method for modeling various versions of the multi-airport GHP. (2) The fundamental result of the thesis is that optimal ground-holding policies seem to be implemented with relative ease and would probably result in a significant alleviation of the congestion problem.

Thesis submitted to the Department of Ocean Engineering, Massachusetts Institute of Technology, in partial fulfillment of the requirements for the degree of Doctor of Science in Operations Research. The thesis advisors were Professors Dimitris Bertsimas and Amedeo Odoni.

Decomposition and Parallel Solution of Network-Structured Optimization Problems

MUSTAFA C. PINAR

Optimization problems characterized by an *embedded* network structure in the constraint matrix are frequently used as a modeling tool in many diverse application areas such as transportation, logistics, finance, telecommunications and so on. We develop techniques that exploit the special structure present in this class of problems. A solution methodology where we propose to place the complicating or *side* constraints into the objective function using the 1-norm penalty function is developed. Thus we obtain a nondifferentiable penalty problem with network constraints. We develop smoothing techniques for the 1-norm penalty function and establish their properties. By using a quadratic smoothing term we obtain a nonlinear nonseparable problem with network constraints. The penalty problem is solved iteratively using a decomposition technique based on a simplicial decomposition of the network constraint set. This decomposition scheme induces separability in the objective function through linearization in the subproblem phase and a nonlinear nonseparable master problem is solved based on the information obtained from the subproblem phase. We develop two specializations of the algorithm: (1) for the network flow problem with side constraints. (2) for the multicommodity flow problem. We present numerical results with Patient Distribution Systems (PDS) multicommodity flow problems and with network flow problems with side constraints derived from matrix estimation problems and the NETLIB Linear Programming Library problems.

The decomposition is particularly suitable for vector multiprocessors systems. We develop a parallel implementation of the linear-quadratic penalty algorithm. Numerical results with a set of larger linear multicommodity network flow problems drawn from a military planning application are presented. The impact of parallel

decomposition is investigated using a CRAY-MP supercomputer system and a Connection Machine CM-2. The parallelism is exploited both at the *tightly coupled* linear algebra level in the master problem and at a *loosely coupled* level with the network subproblems. *Data-level* parallel computing is explored on a massively parallel SIMD system, the Connection Machine CM-2.

As alternatives to simplicial decomposition, two decomposition techniques (1) based on the truncated Newton algorithm (2) on a cyclic decomposition are also considered. The truncated Newton based decomposition is developed for the single commodity case.

We conclude the thesis with an application drawn from Naval Personnel Assignment formulated as a large network model with side constraints and solved using the linear-quadratic penalty technique.

Thesis submitted to Systems Graduate Group, University of Pennsylvania, in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The thesis advisor was Professor Stavros A. Zenios.

The Role of Advanced Traveler Information Systems in Incident Management

HAITHAM MOHAMMED AL-DEEK

Advanced traveler information systems (ATIS) have been proposed recently as a promising technology for improving the efficiency of urban transportation networks and reducing traffic congestion. The dissertation deals with an important application of ATIS technology: the management of incidents.

An off-peak incident is analyzed using deterministic queueing methods in an idealized corridor composed of two routes. A user equilibrium strategy is implemented to disseminate real time traffic information to vehicles equipped with ATIS. The findings show that a few cases of queue evolution result when ATIS is used under incident conditions. Both the proportion of guided traffic and the incident duration play an important role in determining which case results. When an incident occurs, ATIS will divert all equipped vehicles to the alternate route until equilibrium is achieved. Equilibrium is maintained by reducing the rate of diversion from one route to the other through pulsed diversion of ATIS equipped vehicles. The implication is that during equilibrium some ATIS equipped vehicles will be diverted to an alternate route while others will remain on the route where the incident has occurred.

The user benefits follow similar characteristics for all the cases studied. Guided traffic is better off than unguided traffic only during the diversion period that precedes equilibrium, but this advantage is drastically reduced when a queue forms on the alternate route or where equilibrium can be achieved. System benefits increase with the fraction of guided traffic as long as it is below the critical value that causes a queue on the alternate route, but system benefits saturate when this value is exceeded. Also, system benefits do not increase with the proportion of guided traffic in cases where equilibrium can be achieved. The critical fraction does not depend on the incident parameters but does depend on two corridor parameters: the capacity of the alternate route and the corridor demand. The critical fraction equals zero when there is no alternate route and equals one in corridors with several major arterials, usually parallel to the main facility, that can absorb the corridor demand without being congested.

The study findings suggest that route guidance has a significant role in the management of incidents during the off-peak period, when uncongested alternate routes are likely to be available. During the peak period, however, the alternate routes are usually congested, and consequently there is a need to spread traffic over time rather than space. This can be achieved through departure time switching rather than route switching. Here the role of ATIS is thought to be more useful before starting a trip rather than en-route. Pre-trip traffic information permits the most flexible decisions by trip makers. Travelers can switch routes, departure times, and possibly modes. This area is yet to be investigated and is an interesting subject for future research.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Engineering at the University of California at Berkeley. The thesis advisor was Professor Adib Kanafani.

An Investigation and Development of a Combined Traffic Signal Control-Traffic Assignment Model

MOHAMMED SALEH AL-MALIK

The modeling and optimization of the interaction between the assignment of traffic flows in an urban network and the signal controls at the intersections of the network has long been considered an important and challenging problem. The conventional approach has been to treat each problem independently, assuming it is unaffected by the other: traffic lights are set assuming given constant volumes while demands are assigned to routes assuming fixed signal settings. This approach is obviously unsatisfactory since traffic volumes and signal settings are mutually interdependent. Attempts to solve this problem by iteration have also been unsatisfactory: either the problem does not converge or, if it converges, it does not attain an optimal solution.

In this thesis, for the first time, an optimization model is developed that *simultaneously* accounts for both route choice behavior and optimal signal controls. In fact, since the signal timings at the intersections are directly determined by the approach volumes, the signal control variables can be expressed as equivalent flow variables. Thus is obtained an optimization model formulation that inherently reflects the mutual consistency between traffic

volumes and signal settings. Both fixed-time signals and demand-responsive signals can be considered by the model.

At first, only signal splits are being optimized. Cycle time is fixed and offsets are not considered. Performance functions are constructed on the basis of both Webster's queueing delay theory and the Highway Capacity Manual formula. The resulting Combined Model formulation is a nonconvex optimization problem that produces multiple equilibria. Under practical conditions, this problem can be alleviated by a suitable modification of the two Wardropian principles. The demand flows are divided into those that are unaffected by the signal controls (the *ambient* flows) and into those that are subject to influence by the signal controls (i.e., a change in signal timings will cause a change in route choice). Computational results are provided for a sample networks with both user-optimization and system-optimization model formulations.

The last chapter considers coordinated signal networks with offset optimization. This adds another layer of complexity to the combined traffic signal control-traffic assignment model. Two iterative procedures are investigated. In the first procedure, assignment and split optimization is carried out simultaneously as before, then iterated with offset optimization by the TRANSYT model. *A Progression Adjustment Factor* is used to link the two parts of the iteration. The Factor adjusts the link performance function in accordance with the quality of progression established by the offset optimization. In the second procedure, only TRANSYT optimization for both splits and offsets is iterated with an assignment procedure. It is shown that improved performance can be achieved with the simultaneous model.

Thesis submitted to the academic faculty at the Georgia Institute of Technology in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Civil Engineering. The guest thesis supervisor was Nathan H. Gartner of the University of Massachusetts, Lowell.

Toward a Model of Activity Program Generation

CHANDRA BHAT

Activity-based travel analyses have gained popularity in recent years because they recognize the complexity of activity behavior and view travel as a derivative of this behavior. Most activity-based studies have focused on the spatial and temporal linkage of trips; that is, the scheduling of activities. They consider the agenda (or program) of activities for participation, and associated attributes of the activity participation (such as a mode to activity and location of activity performance) as predetermined. This dissertation develops a comprehensive conceptual framework of the relatively unexplored area of activity agenda generation: the process by which individuals select activities for participation and the associated attributes of activity participation. The framework accounts for the interrelationship between activity agenda generation and activity scheduling. Such a framework will be valuable to a comprehensive theoretical and empirical treatment of activity-travel behavior. The dissertation also takes an important step toward building a structural and empirical model of activity generation behavior based on the conceptual framework.

The individual activity program generation process is conceptualized as comprising four main modules. The first module—the Household Needs Module—deals with the generation of subsistence and maintenance needs of the household. Subsistence activity refers to work-related activity and includes the employment decision and hours of work decision of individuals in a household. Maintenance activity pertains to the purchase and consumption of goods and services to satisfy household and personal physiological and biological needs. Maintenance activities include grocery shopping, personal business (banking, going to the post office, etc.), and household work (cooking, cleaning, child supervision, etc.). The second block—the Household Auto Ownership Module—conceptualizes the forces that determine auto ownership choice. The first two modules influence the third module —the Allocation Module—that describes the allocation of automobiles and household maintenance needs among household members. The fourth and final module—the Activity Programming Module—captures the implicit planning process by which individuals accomplish and complete their personal needs and allocated activities and decide on participation in leisure activities. Leisure activities refers to social, recreational and other discretionary pursuits motivated by cultural and psychological needs. This module determines the attributes (mode, location, frequency, duration, and time window) of participation in personal and allocated out-of-home maintenance activities and participation attributes in out-of-home leisure activities.

The output from the generation process is an agenda of activities for participation along with the attributes of frequency, duration, destination of activity performance, mode to destination and time-window for participation. This activity program can form the input to activity scheduling models. Thus, the combination of the activity program generation model developed here and the activity scheduling models developed earlier provide a theoretical basis for the analysis of travel behavior and travel demand.

The empirical model of the dissertation focuses on the formulation and estimation of an integrated model of subsistence activity, income and household car ownership which takes account of interdependencies among these choices and their structural relationships with relevant exogenous variables. The model is based on the conceptualization of the activity program generation process. The analysis is conducted using a sample of nuclear family households from the Netherlands. The procedure

used to estimate the simultaneous system of subsistence activity, income, and car ownership explicitly accommodates the grouped (or interval-level) observation on income (which is a general characteristic of almost all transportation-related databases), the observation of hours of work and income conditional on employment, and the correlation in unobserved factors that affect employment decisions of individuals in a household and household car ownership.

In addition to its value as an element of the activity generation framework, the empirical model developed here is useful for trip-based demand estimation and forecasting. Traditional trip-based models (car ownership models, trip generation models, mode choice models, etc.) do not account for the grouped observation on income or the correlation in unobserved factors that simultaneously affect subsistence activity choices and travel-related choices in the estimation phase. This could lead to inconsistency of parameter estimates in the travel or travel-related behavioral model under consideration (car ownership in the current empirical model). Even ignoring this inconsistency in estimation, traditional models still encounter the problem of obtaining reliable forecasts of employment and income needed to obtain reliable forecasts of travel-related variables. Traditional methods use simple aggregate-level forecasts of employment and income, which fail to adequately capture the influence of demographic and other factors affecting these variables. On the other hand, a causal disaggregate model of employment and income addresses the behavioral factors underlying employment decisions and income earnings and thus provides a reliable forecast of employment and income (and therefore a reliable forecast of travel demand).

Thesis submitted to the Graduate School, Northwestern University, in partial fulfillment of the requirements for the degree of Doctor of Philosophy, Field of Civil Engineering. The thesis advisor was Professor Frank S. Koppelman.

High-Throughput Intermodal Containers Terminals Technical and Economic Analysis of New Direct-Transfer System

BERNARDO J. DE CASTILHO

The volume of containerized cargo traffic has increased steadily over the last three decades. Because of significant cost advantages on long-haul trips and growing concern for the environment, large portions of this traffic are now transported by trains rather than trucks. The main stumbling block that has prevented rail transportation from playing an even more prominent role in the movement of containerized cargo has been the interface between vessels and trains. Traditionally, trucks are used to transport containers between the port and remote rail yards, but their process is rather expensive. This research explores innovative systems capable of performing such transfer operations more directly and efficiently.

Terminals with rail tracks along the docks—allowing for trains to be loaded directly from ships—are common for bulk cargo, but have not to date been implemented successfully for containerized cargo. The main reasons for this are (i) the need to classify the trains by container destination and (ii) reduced dock crane throughput due to interference while multiple cranes try to unload containers onto a single rail track.

The main thrust of the research is the development of a direct-transfer terminal design that allows trains to be loaded and simultaneously classified by destination, largely eliminating the need for further train processing at downstream railyards. The design features multiple railtracks along the docks, straddled by double-hoist dock cranes provided with the internal buffers that decouple the waterside from the landside operations. Pusher tractors are used to position strings of railcars so that containers being unloaded from the ships are positioned adjacent to others bound for the same destination. The system allows for simultaneous ship unloading and train sorting.

Analytical methods are developed to evaluate the performance of the proposed design, including train classification levels attainable during the loading process and the productivity of the dock system. Train sorting levels are measured in terms of the expected number of cuts required to separate the train into segments bound for the same destination. The productivity of the dock system is measured as a percentage of the maximum productivity attainable if the dock cranes could operate independently of land side processes.

The methods developed allow the expected number of cuts per railcar and the expected dock productivity to be estimates as functions of the number of destinations for the containers aboard a typical ship, the number of tracks to be used in the ship unloading process, the level of sorting of the containers aboard the ship, the length of the strings of railcars that can be handled under the dock cranes at one time, and the size of the dock crane's internal buffer.

The methods presented are based on queuing techniques, probability, and statistics. The formulas obtained are validated against a detailed computer simulation, also described in the text.

A comprehensive economic model is developed to measure the costs incurred by the terminal operator, shippers, and railroads while moving containers through the proposed terminal and through conventional facilities. The model includes factors that are often neglected in the literature, such as the inventory costs of loaded containers aboard the ship. Other important cost factors include equipment capital and maintenance costs, labor, and land costs. A significant portion of the effort in this research was dedicated to the collection and compilation of realistic estimates for each of these costs.

Several operating scenarios are used to identify the conditions under which each type of terminal design is most effective. The results show that direct-transfer terminals can be more cost-effective than conventional approaches, especially in cases where a significant portion of the traffic is intermodal. The savings are mainly due to the reduced handling and inventory costs, but the proposed design also has advantages from an environmental viewpoint and lends itself very well to automation.

It would be naive to expect the solutions suggested to be directly applicable to any particular container terminal. Instead, it is hoped that elements of the proposed design and analytical methods presented could be used in the development of customized solutions for individual facilities.

Thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Engineering at the University of California at Berkeley. The thesis advisor was Carlos F. Daganzo.

Delay Estimation on Congested Waterways

MELODY DZWO-MIN DAI

A simulation model has been developed for estimating delays on congested waterways and a numerical method has been developed to approximate the results of the simulation model. The structural relations in the numerical method were largely based on exact analytic results from queueing theory while their unknown parameters were estimated statistically from the simulation model. The numerical method is valuable for screening improvement alternatives, while the simulation model is valuable for very detailed and accurate analysis.

The simulation model is microscopic and event-scanning. It can accommodate generally distributed trip generations and service times, unequal parallel servers, and random failure effects. Its outputs include tow travel times along waterways, tow delays at each lock, inventory levels, expected stock-out amounts for commodities transported on waterways, and variances of interarrival and interdeparture times at each lock. The simulation model has been validated in comparisons with established theoretical results and empirical data from the U.S. inland waterways.

The numerical method decomposes waterway systems into single lock queueing stations and then scans along waterways to analyze the interarrival-time and interdeparture-time distributions at each lock. Lock interdependence is accounted for since interarrival times at each lock are affected by the interdeparture times from adjacent locks.

The numerical method includes modules for arrivals, departures, and delays. The arrivals module identifies the effects of departures from two adjacent locks and speed distributions on the combined interarrival-time distribution. The departures module estimates the variance of interdeparture times for each direction. The delays module estimates the average waiting time for each lock when the means and variances of its overall interarrival, interdeparture, and service times are known. The method can be applied to systems with two-way traffic through common bi-directional servers, as well as to one-way traffic systems. Algorithms for both cases are presented. This numerical method is shown to produce results that closely approximate the simulation results.

Thesis submitted to the faculty of the Graduate School, University of Maryland at College Park, in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The thesis advisor was Professor Paul Schonfeld.

A Study of Monotone Variational Inequalities and Their Application to Network Equilibrium Problems

JIA HAO WU

In this thesis, we consider the finite monotone variational inequality problem *VIP* in a systematic way and its application to network equilibrium problems. *VIP* consists in finding a solution $v^* \in \Omega \subset \Re^m$ which satisfies $s(v^*)^T(v - v^*) \geqslant 0$, for all $v \in \Omega$. The current state of research into theory and algorithms in this field is reviewed. The *VIP* plays a significant role in many applications such as in economics and transportation in addition to several academic fields. An equivalent optimization problem of *VIP* is formulated. Based on it, a general descent framework for the problem is established with a proof of its convergence. Several realizations of the framework are also discussed to indicate its relationship to some existing algorithms. An inexact descent algorithm is also proposed. A similar analysis is applied to a transformed monotone variational inequality problem VIP_h where the cost function is only monotone. The developed framework then is applied to the network equilibrium problem where the cost structure is asymmetric. Some specific algorithms are presented with respect to the network structure. In what follows, we establish a model for transit equilibrium assignment. The model is then formulated as VIP_h and is solved with both a linearized Jacobi method and a projection method. Finally, numerical results are reported. The conclusions are given with possible research opportunities and general comments.

In short, the contributions of the thesis are:

1. A literature review of the *VIP* theory and algorithms is given;
2. A general descent framework for the *VIP* equivalent optimization problem is established with a detailed analysis;

3. An inexact method is developed for the *VIP*;
4. A similar analysis is applied to the VIP_h;
5. A global convergence proof is given for the linearized Jacobi method for VIP_h;
6. An efficient algorithm is developed for a special quadratic program;
7. A model for the transit equilibrium assignment is established and formulated as VIP_h

and is solved with the linearized Jacobi method. And the numerical results are reported.

Thesis submitted to the Department d'Informatique et de Recherche Operationelle, Université de Montréal, in partial fulfillment of the requirements for the degree of Doctor of Philosophy. The thesis advisors were Professors Michael Florian and Patrice Marcotte.