ISSUED TO INCORPORATE PROFS MEMO DATED 9/21/92 REDUCING FUNDS BY $64,700. PI HAS TRANSFERRED PROJECT TO MIT. $64,700 TRANSFERRED TO MIT.
GEORGIA INSTITUTE OF TECHNOLOGY
OFFICE OF CONTRACT ADMINISTRATION

NOTICE OF PROJECT CLOSEOUT

Closeout Notice Date 01/28/93

Project No. E-24-616__________
Project Director BARNHART C__________
Sponsor NATL SCIENCE FOUNDATION/GENERAL______________
Contract/Grant No.,DDM-9058074______________

Project Director BARNHART C__________
School/Lab ISYE__________

Sponsor NATL SCIENCE FOUNDATION/GENERAL______________
Contract/Grant No.,DDM-9058074______________

Prime Contract No. 

Contract Entity GTRC

Title PYI____________________________

Effective Completion Date 960229 (Performance) 960530 (Reports)

---

Closeout Actions Required:          Date Submitted

Final Invoice or Copy of Final Invoice   N
Final Report of Inventions and/or Subcontracts   N
Government Property Inventory & Related Certificate   N
Classified Material Certificate   N
Release and Assignment   N
Other _______________________________   N

Comments
EFFECTIVE DATE 9-1-90. CONTRACT VALUE 85,300.
NOTE: THIS PROJECT HAS BEEN TRANSFERRED TO MIT AS OF 9-1-92.

Subproject Under Main Project No. 
Continues Project No. 

Distribution Required:

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<td>Administrative Network Representative</td>
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<td>Other HARRY VANN-FMD</td>
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<td>FRED CAIN-OOD</td>
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</table>
April 5, 1991

Ms. Carol Guido
National Science Foundation
Division of Design and Manufacturing Systems
Room 1128
1800 G St. N.W.
Washington, D.C.  20550

Dear Carol:

Attached is the budget and progress report for my Presidential Young Investigator Award entitled "Large-Scale Problems in Transportation, Distribution and Logistics," Grant Number DDM-9058074.

The $55,000 budget includes $30,000 matching for funding provided by IBM and $25,000 for the base funds for 1991-1992.

If you have any questions, please give me a call at (404) 894-2325. Thank you.

Sincerely,

Cynthia Barnhart, Ph.D.
This multi-year research project focuses on the application of operations research methods to large-scale problems in Transportation, Distribution and Logistics. The scope of the project includes model formulation, algorithmic development, computer implementation and computational testing.

In 1990-1991, the focus was on the development of alternative solution strategies for large-scale multi-commodity network flow problems and long-haul crew assignment problems.

Large-Scale Multi-Commodity Network Flow Problems

Multi-commodity network flow problems, prevalent in transportation, production and communications, are characterized by a set of origin-destination flows or commodities and an underlying network. The objective is to flow the commodities through the network at minimum cost without violating the capacity constraints on network arcs. We develop a new cycle-based formulation and solution procedure for large-scale multi-commodity flow problems, particularly those with many commodities. The procedure determines an optimal multi-commodity flow solution by reformulating the problem; relaxing a large number of constraints; and solving a
series of reduced-size linear programs using column-generation.

Computational results are obtained for a communications problem involving hundreds of commodities and methods for obtaining integer solutions are under development.

This research will be presented at the ORSA/TIMS Conference in May 1991 and, by invitation, at the 14th International Symposium on Mathematical Programming in August 1991. The paper describing this work will be submitted to Operations Research in the Summer of 1991.

Long-Haul Crew Assignment

The inputs to the long-haul crew assignment problem include a planning horizon (e.g., one month for long-haul problems); crew base locations; and flight services, typically international, with specified departure and arrival times at fixed origin and destination points. The objective is to assign one crew to cover each flight service such that overall costs are minimized and crew availability and work rules restrictions are not violated.

We model the long-haul crew assignment problem as a linear multi-commodity network flow problem, where each commodity represents a set of crews located at a crew base at a point in time, and the arcs of the underlying network reflect all possible legal crew assignments to flight services. The network was generated so that each network path represents a legal crew pairing, i.e., a sequence of flight services satisfying work rule restrictions that begins and ends at a crew base. Then, the multi-commodity objective of finding the cost-minimizing assignment of
commodity flows to network paths is equivalent to determining the cost-minimizing assignment of crews to flight services.

For each flight service, two nodes and a connecting "service" arc is included in the network. The tail node represents the flight's origin location at the time of its departure and the head node represents the flight's destination location at its arrival time. The connecting service arc represents the scheduled flight service to which a crew must be assigned. To include all possible legal crew assignments in the network, additional service arcs are added, each one corresponding to a string of flight services uninterrupted by rest. These strings, often called duty periods, must satisfy work rule restrictions when assigned to a single crew.

In addition to service arcs, the network contains layover arcs. Layover arcs, representing the possibility that a legal pairing may require crews to stay in one location for a period of time, span two nodes representing different times and a single location.

All arc costs are set equal to the time difference associated with the head and tail node of the arc. This reflects the assumption that, for long-haul crew assignment problems, the time-away-from-base rule typically determines crew assignment cost. (The time-away-from-base rule requires the cost of any crew assignment to be a function of the elapsed time from the departure of the crew from their base to their arrival back at the base.)

We solve the linear crew assignment problem using column generation techniques, specifically price-directive decomposition. The first set of columns included in the linear program (LP) are
determined using a heuristic to generate initial feasible solutions. Solution of the initial LP provides dual prices to be used in modifying network arc costs and generating additional LP columns. Columns for inclusion in the LP are generated using a shortest path procedure over the modified cost network. Further efficiencies are gained by using a specialized shortest path procedure exploiting the time-based structure of the network.

We are currently developing methods to obtain integer solutions and conducting computational experiments using data provided by a long-haul operating airline.

We have been invited to present this research at the Triennial Symposium on Transportation Analysis in June 1991 and, at that time, the paper describing this work will be submitted to Transportation Science.
### Cover Sheet for Proposals to the National Science Foundation

**Division of Design & Mfg. Systems**

**Employer Identification Number (EIN) or Taxpayer Identification Number (TIN):** 53-0603146

**Show Previous Award No. If This Is: □ A Renewal or □ An Accomplishment-Based Renewal**

**Is This Proposal Being Submitted to Another Federal Agency?**

---

**Name of Organization to Which Award Should Be Made:**

**Georgia Tech Research Corporation**

**Address of Organization (Include Zip Code):**

**Georgia Institute of Technology**

**Atlanta, Georgia 30332-0420**

**Organization Category:**

- □ For-Profit Organization
- □ Small Business
- □ Minority Business
- □ Woman-Owned Business

**Branch/Campus/Other Component (Where Work Is Performed, If Different):**

**Institution Code (If Known):** 0015693000

---

**Title of Proposed Project:**

- Presidential Young Investigator Award
- "Large-Scale Problems in Transportation, Distribution and Logistics"

**Requested Amount:** $55,000

**Proposed Duration (in months):** One Year

**Requested Starting Date:** As soon as possible

---

**Check Appropriate Boxes If This Proposal Includes Any of the Items Listed Below:**

- □ Vertebrate Animals
- □ Human Subjects
- □ Research Involving Genetically Engineered Organisms
- □ National Environmental Policy Act
- □ Proprietary and Privileged Information
- □ International Cooperative Activity
- □ Historical Places

**Country/Regions:**

---

**P.I./P.D. Phone Number/Electronic Mail Address:**

- (404) 894-2325
- cbarnhart@grtl@1.bitnet

**P.I./P.D. Fax Number:** (404) 894-2301

**Names (Typed):**

- **Co-P.I./P.D.**
- **Co-P.I./P.D.**
- **Co-P.I./P.D.**
- **Co-P.I./P.D.**
- **Co-P.I./P.D.**

**Social Security No.:**

**Highest Degree & Year:** Ph.D., 1988

**Signature:**

---

**By signing and submitting this proposal, the individual applicant or the authorized official of the applicant institution is providing the certifications regarding Federal debt status, debarment and suspension, drug-free workplace, and lobbying activities, as set forth in Grants for Research and Education in Science and Engineering: NSF 90-77 (8/90).**

---

**Telephone Number:** (404) 894-4817

**Electronic Mail Address:**

**Fax Number:** (404) 894-3120

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*Submission of social security numbers is voluntary and will not affect the organization’s eligibility for an award. However, they are an integral part of the NSF information system and assist in processing the proposal. Section 337h contained under NSF Act of 1950, as amended*

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**NSF Form 1227 1-90**
NATIONAL SCIENCE FOUNDATION
PRESIDENTIAL YOUNG INVESTIGATOR AWARDS PROGRAM
REQUEST FOR BASE AND/OR MATCHING FUNDS

<table>
<thead>
<tr>
<th>PYI NAME:</th>
<th>Cynthia Barnhart</th>
<th>DATE of REQUEST</th>
<th>April 5, 1991</th>
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<tr>
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<td>YEAR OF PYI AWARD</td>
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DESCRIPTION OF REQUESTS

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<td>1 2 3 4 5 $26,700 $3,300</td>
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DATE RESEARCH ACTIVITY INITIATED | September 1990

MATCHABLE SOURCES
(LISTED INDIVIDUALLY)

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NOTES:
The NSF base award is $25,000; the maximum amount of matching funds is $37,500 for each activity year. Research activity must start by October 1, of award year. The awardee must designate starting date for research activity.

SOURCE CODES*

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<td>E23 Local government</td>
<td>H50 US Citizen or President</td>
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<td>I64 Foreign Organization</td>
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September 17, 1990

Dr. Cynthia Barnhart
Assistant Professor
Industrial and Systems Engineering
Georgia Institute of Technology
Atlanta, Georgia  30332-0205

Dear Dr. Barnhart:

Funding will be provided to you by IBM in the amount of $30,000.00 for your work in large-scale network optimization. This funding will cover the period between September 1990 and September 1991.

It is hoped that you will be able to obtain matching funds for this project through NSF's Presidential Young Investigator program.

Sincerely,

Herbert J. Schultz
Manager, Optimization Subroutine Development

/pf
# SUMMARY PROPOSAL BUDGET

## ORGANIZATION
Georgia Tech Research Corporation

## PRINCIPAL INVESTIGATOR/PROJECT DIRECTOR
Cynthia Barnhart

### A. SENIOR PERSONNEL: PI/PO, Co-PI's, Faculty and Other Senior Associates
(List each separately with title, A.6. show number in brackets)

<table>
<thead>
<tr>
<th>Name</th>
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<th>INDUSTRIAL MATCHING</th>
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<td>$7,621</td>
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### B. OTHER PERSONNEL (SHOW NUMBERS IN BRACKETS)

1. ( ) Post Doctoral Associates
2. ( ) Other Professionals (Technician, Programmer, etc.)
3. ( ) Graduate Students @ $2248/Qtr 1/3 t., 4 Qtrs $8,992
4. ( ) Undergraduate Students
5. ( ) Secretarial Clerical
6. ( ) Other

### D. PERMANENT EQUIPMENT (LIST ITEM AND DOLLAR AMOUNT FOR EACH ITEM EXCEEDING $1,000:)

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### E. TRAVEL

1. Domestic (Incl. Canada and U.S. Possessions) $1,000
2. Foreign $1,000

### F. PARTICIPANT SUPPORT COSTS

1. Stipends $639
2. Travel
3. Subsistence
4. Other

### G. OTHER DIRECT COSTS

1. Materials and Supplies $639
2. Publication Costs/Documentation/Dissemination
3. Consultant Services
4. Computer (ADPE) Services
5. Subcontracts
6. Other

### H. TOTAL DIRECT COSTS (A THROUGH G)

$50,300

### I. INDIRECT COSTS (SPECIFY RATE AND BASE)

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<td>Industrial Funds</td>
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### J. TOTAL DIRECT AND INDIRECT COSTS (H I)

$55,000

### K. RESIDUAL FUNDS (IF FOR FURTHER SUPPORT OF CURRENT PROJECTS SEE GPM 252 AND 253)

$55,000

### L. AMOUNT OF THIS REQUEST (J) OR (J MINUS K)

$30,000

---

*SIGNATURES REQUIRED ONLY FOR REVISED BUDGET: GPM 233.

WILL BE COST-SHARED IN ACCORDANCE TO NSF POLICY

---

NSF Form 1030 (8/90) Supersedes All Previous Editions.
May 11, 1992

Ms. Carol Guido
National Science Foundation
Division of Design and Manufacturing Systems
Room 1128
1800 G St. N.W.
Washington, D.C. 20550

Dear Carol:

Attached is the budget and progress report for my Presidential Young Investigator Award entitled "Large-Scale Problems in Transportation, Distribution and Logistics," Grant Number DDM-9058074.

If you have any questions, please give me a call at (404) 894-2325. Thank you.

Sincerely,

Cynthia Barnhart, Ph.D.
This multi-year research project focuses on the application of operations research methods to large-scale problems in Transportation, Distribution and Logistics. The scope of the project includes model formulation, algorithmic development, computer implementation and computational testing.

In 1991-1992, the focus was on the development of models and solution strategies for long-haul crew scheduling, intermodal routing, distribution system design, and large-scale multi-commodity network flow problems.

Long-Haul Crew Scheduling

The crew assignment problem is characterized by a set of flight segments, work rules restricting crew utilization, crew availability limitations, and costs for every flight expressed as a function of time. The objective is to assign one crew to each scheduled flight such that overall costs are minimized and crew availability and work rule restrictions are satisfied. A long-haul crew assignment problem is characterized by flight segments that are typically long distance and do not operate on a daily schedule.

We solve the long-haul crew assignment problem by a two-phase
process. In the first phase, the integrality constraints are relaxed and the resulting linear program is solved using column generation. Columns are efficiently determined using a specialized shortest path procedure on a long-haul network. The network is constructed so that certain network paths correspond to crew pairings. In the second phase of the solution procedure, an integer crew assignment is determined using a general purpose mixed-integer programming package. Future research efforts will involve the development of a specialized procedure to determine integer solutions using column generation.

Deadhead Selection

Long-haul crew scheduling problems are characterized by international flights that typically do not operate on a daily schedule, resulting in sparsity of flights and extended periods of inactivity for crews at some stations. To eliminate these extended rest periods and reduce overall costs, it is advantageous in some cases to deadhead crews, that is, to assign crews to flights as passengers for repositioning and better utilization.

We developed a methodology to improve crew assignment solutions through the efficient selection and utilization of deadhead flights. The methodology uses the dual solutions determined in solving the linear programming relaxation of the crew assignment problem to build arrival and departure profiles at each station. These profiles provide a mechanism to price-out potential deadhead flights. Flights that price-out favorably may be used to
build improved solutions to the crew assignment problem.

Using data provided by a long-haul operating airline, our new long-haul crew scheduling and deadhead selection procedure was tested and shown to achieve savings measuring over $5,000,000 annually. In addition to generating more efficient crew schedules through the effective selection of deadhead flights, the deadhead selector successfully reduced the total amount of deadhead flying time.

This research was presented at the following conferences or seminars: ORSA/TIMS (May 1991), Northwestern University Seminar (May 1991), the Triennial Symposium on Transportation Analysis (June 1991), IBM Watson Research Center Seminar (September 1991), the 1992 NSF Design and Manufacturing Systems Grantees Conference (January 1992), and TIMS/ORSA (May 1992). The attached papers entitled "A Column Generation Technique for the Long-Haul Crew Assignment Problem" by C. Barnhart, E.L. Johnson, R. Anbil and L. Hatay and "Deadhead Selection for the Long-Haul Crew Pairing Problem" by C. Barnhart, L. Hatay, and E.L. Johnson were submitted to Transportation Science in June 1991 and Operations Research in January 1992, respectively.

Intermodal Routing

An intermodal shipment is one that uses more than one mode of transportation. While there are a variety of mode combinations that are utilized by shippers, our focus is on modeling the
truck/rail combination. Intermodal shipping via truck and rail currently has a monthly average of more than 100,000 trailers and containers originating in the United States each month. The biggest obstacles to dramatically increasing intermodal shipping is the lack of innovative pricing which would allow shippers to utilize intermodal in conjunction with direct truck load shipping. Our research addresses the issue of how optimally to route intermodal shipments considering both intermodal and direct truck load options. The results can also be used as the basis for determining pricing strategies to make intermodal shipping competitive with direct truck load shipments over a wider range of potential business.

Given the assumption that a flatcar can transport up to two trailers simultaneously and that total intermodal costs are expressed per trailer or per flatcar, the optimal routing of each trailer from its origin to its destination can be determined efficiently using network-based solution procedures. In the case of rail costs expressed per trailer, the minimum cost routings are achieved with a shortest path procedure. For rail costs expressed per flatcar, the optimal routings are determined with a matching or b-matching algorithm. Finally, the solution procedures allow schedule requirements and flatcar configuration considerations to be modeled in a straightforward manner.

Shortest path and matching procedures implemented even on small computers can solve large problems quickly. Thus, these models provide a practical means for automating the intermodal

**Distribution System Design**

The objective of our research was to demonstrate with a real application the practical importance of the need for good formulations in solving mixed-integer programming problems. The application was a large-scale distribution system consisting of a network with plants, intermediate distribution facilities referred to as replenishment centers, and demand points called distribution centers. A different product group is produced at each plant and there may be up to three available transportation modes, i.e., truck, train or trailer on a flat car, between any pair of replenishment and distribution centers.

A standard formulation of a real-world distribution problem could not be solved, even for a good solution, by a commercial mixed-integer programming code. However, after reformulating it by reducing the number of 0-1 variables and tightening the linear programming relaxation, an optimal solution could be found efficiently.
The paper entitled "Solving a Large-Scale Distribution Problem: A Real Example of Using a Good Formulation to Solve a Mixed-Integer Program" by C. Barnhart, E.L. Johnson, G.L. Nemhauser, G. Sigismondi, and P. Vance was submitted to *Operations Research* in April 1992.

**Large-Scale Multi-Commodity Network Flow Problems**

Multi-commodity network flow problems, prevalent in transportation, production and communication, can be characterized by a set of origin-destination flows, i.e., commodities, and an underlying network. The objective is to flow the commodities through the network at minimum cost without exceeding the capacity of any arc. We develop an iterative solution procedure for large-scale multi-commodity flow problems, particularly those with many commodities. The procedure determines an optimal multi-commodity flow solution by formulating the problem using a cycle-based representation; relaxing a large number of constraints; and solving a series of reduced-size linear programs using column generation. Each subsequent solution generated is an improved basic dual feasible solution and, after a finite number of steps, the optimal multi-commodity flow solution is determined.

Our solution procedure was validated using message routing test problems provided by a telecommunication firm. The message routing problem objective is to find the minimum cost flow of messages through an undirected network. Each message has a
specific origin point and a specific destination point and routing costs are a linear function of the number of messages sent. To evaluate the effects of varying levels of congestion (i.e., total commodity flow) in the network, 12 message routing problems were solved over the same network with demand for every commodity increased by 10% in each subsequent problem. Solutions to these problems provide insight concerning the capacity of the telecommunication network and the impact on overall system performance of variations in the number of messages.

Our future research efforts focus on using our new solution methodology to find integer solutions to the multi-commodity flow problem, that is, to find solutions satisfying the requirement that flow for each commodity is exclusively assigned to one source to sink path. This is not a typical integer programming problem in that our linear program has many columns and only a relatively small number are generated in the LP solution process.

Dual-Ascent Heuristics

To determine approximate multi-commodity flow solutions to large-scale problems, we developed dual-ascent heuristics and a primal solution generator. The dual-ascent solutions, in addition to determining lower bounds on the optimal objective function value, provide advanced starting solutions for use with primal-based solution techniques. The primal solution generator uses the dual-ascent solution to obtain heuristic primal solutions to the multi-commodity flow problems.
Computational experiments performed on three test problem sets showed that the dual-ascent and primal heuristic procedures typically determine near-optimal solutions quickly. In addition, by using the dual-ascent procedure to obtain advanced starting solutions, run times for optimal multi-commodity flow procedures are reduced significantly and greatly improved solutions are obtained by the new primal solution generator.

This research was presented at the following conferences or seminars: ORSA/TIMS (May 1991), University of Chicago Seminar (May 1991), the 14th International Symposium on Mathematical Programming (August 1991), and the 1992 NSF Design and Manufacturing Systems Grantees Conference (January 1992). The papers entitled "Dual-Ascent Methods for Large-Scale Multi-Commodity Flow Problems" by C. Barnhart and "An Alternative Formulation and Solution Strategy for Multi-Commodity Network Flow Problems" by C. Barnhart, E.L. Johnson and G. Sigismondi were submitted to the Naval Research Logistics (resubmission April 1992) and to Operations Research (September 1991), respectively.