ITS UCDAVIS
INSTITUTE OF TRANSPORTATION STUDIES

Research Report – UCD-ITS-RR-07-48

# Stochastic Models for Transportation Network Protection: Final Progress Report

September 2007

Changzheng Liu

Institute of Transportation Studies ◦ University of California, Davis
One Shields Avenue ◦ Davis, California 95616
PHONE (530) 752-6548 ◦ FAX (530) 752-6572
www.its.ucdavis.edu

UCDAVIS
SUSTAINABLE TRANSPORTATION CENTER
*of the Institute of Transportation Studies*

# Final Progress Report

*Project Name*: Stochastic Models for Transportation Network Protection

*Project #*: **D01-5**
*PI Name*: **Changzheng Liu**
*Project Start Date*: **Sep. 2006**
*Project End Date*: **Sep. 2007**
*Project Award:$* **30,802**

Congratulations on the completion of your research! To meet the reporting requirements of the Sustainable Transportation Center's funding agencies, and to disseminate information on the STC's projects in various media, we are asking you to complete this *Final Progress Report* on your project.

If you have completed your research, please provide the following:

1) Final Progress Report: Update on personnel, presentations, publications and impacts involved in this research. Please fill out pp. 2-3.
2) Research Brief: 2-page summary of research, as explained on p. 4 and using the template provided on pp. 5-6.
3) Final Product: As described on pg. 7, every project is required to submit a final product, usually a research report published in the ITS online publications database. One or more peer-reviewed papers can serve as the final product, if equivalent information is provided. For some projects, other types of products may be appropriate.

Please complete the entirety of this worksheet and email it to Mary Madison Campbell (memadison@ucdavis.edu) The report is due one month after project completion. Please note we will continue to ask for brief *Project Follow-ups* listing project-derived publications and presentations. These *Follow-ups* are due every March 1 and September 1. Thank you for your time in completing this important information.

Please note that any publications or presentations resulting from STC-funded work are required by grant contract, which is included in the grant proposal paperwork, to contain the following credits, as applicable:

Presentations should include the STC logo and an acknowledgement of STC support.

Peer review papers should include the following statement in the acknowledgements:

*"The research was supported by a grant from the Sustainable Transportation Center at the University of California Davis, which receives funding from the U.S. Department of Transportation and Caltrans, the California Department of Transportation, through the University Transportation Centers program."*

Research reports and working papers should include the above acknowledgement, as well as the following disclaimer:

*"The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents of use thereof."*

## Final Progress Report

## Personnel Information

*Please list all other personnel (researchers, grad students, etc.) who have been involved in this project. Include name & title. Please be sure to include any unpaid volunteer researchers or assistants.*

## Technology Transfer

### Presentations

Please list any presentations resulting from this funding during this reporting period. The PI does not need to be the presenter. This information is needed for federal reporting compliance.

Provide the following for each listing: Presenter, Month/Year, Title, Event, and Location.

*Liu, C. (2009) Transportation Networks Protection under seismic hazards", the Sixth International Conference on Urban Earthquake Engineering, Tokyo, Japan, March 2009*
*Fan, Y. and C. Liu (2008) "Effects of Risk Preferences on Network Design Decision", Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting, Washington, DC, USA, October 2008.*
*Liu, C. and Y. Fan (2008) "Solving the Highway network retrofit problem, the 10th International Conference on Application of Advanced Technologies in Transportation", Athens, Greece, May 2008.*
*Liu, C. and Y. Fan (2007) "A Two-stage Stochastic Programming Model for Transportation Network Retrofit", the 86th Transportation Research Board (TRB) Annual Meeting, Washington, DC, USA, January 2007.*
*Liu, C. and Y. Fan (2007) "Numerical methods for solving stochastic programming with equilibrium constraints", Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting, Seattle, USA, November 2007.*
*Liu, C. and Y. Fan (2007) "Stochastic Transportation Network Retrofit", Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting, Pittsburgh, USA, November 2006.*

### Publications

Please list any publications in progress and completed during this reporting period. The PI does not need to be an author. This information is needed for federal reporting compliance. So we can submit the publications to the online ITS database, please send electronic copies of completed publications to Mary Madison Campbell (memadison@ucdavis.edu).

Please provide as much citation information as you can for each item: Author(s), Year, Title, Publication, Volume, Issue, Pages (or status such as "submitted to but not published"). Please also mark all applicable boxes for each listing.

1) Citation: Fan, Y. and **C. Liu** (2009) Solving Stochastic Transportation Network Protection Problems Using the Progressive Hedging-based Method, *Networks and Spatial Economics*, vol. 10(2), pp. 193-208.

Type:

Y: Peer Reviewed Journal Article
☐ Research Report/Working Paper (provide ITS report number):
☐ General Audience Article

☐ Other (explain):

Status:

☐ Draft in progress
☐ Draft completed
☐ Submitted
☐ Revisions in progress
Y: Published

2) Citation: Changzheng Liu, 2009, "A Stochastic Programming Approach for Transportation Network Protection", Dissertation, the University of California, Davis

Type:

☐ Peer Reviewed Journal Article
☐ Research Report/Working Paper (provide ITS report number):
☐ General Audience Article
☐ Other (explain): Dissertation

Status:

☐ Draft in progress
☐ Draft completed
☐ Submitted
☐ Revisions in progress
Y: Published

3) Citation: Fan, Y. and C. Liu (2009) Solving Stochastic Transportation Network Protection Problems Using the Progressive Hedging-based Method, Networks and Spatial Economics, vol. 10(2), pp. 193-208.

Type:

Y: Peer Reviewed Journal Article
☐ Research Report/Working Paper (provide ITS report number):
☐ General Audience Article
☐ Other (explain):

Status:

☐ Draft in progress
☐ Draft completed
☐ Submitted
☐ Revisions in progress
Y: Published

4) Citation: Fan, Y. and C. Liu, R. Lee, and A. Kiremidjian (2010) Highway Network Retrofit under Seismic Hazard, Journal of Infrastructure Systems Vol. 16(3), pp. 181-187.

Type:

Y: Peer Reviewed Journal Article
☐ Research Report/Working Paper (provide ITS report number):
☐ General Audience Article
☐ Other (explain):

Status:

- ☐ Draft in progress
- ☐ Draft completed
- ☐ Submitted
- ☐ Revisions in progress
- Y: Published

**Please copy and paste if you have more publications to list.**

## Impact Indicators

Please list any indications you have that your research project has been used or referenced by others. Our federal funders require anecdotal reports on the impacts of STC research to policy or practice in the transportation fields. Indications may include changes to technologies as a result of your research; government policy decisions that were influenced by it; or inquiries about the research from non-academic professionals. Please also indicate any media inquiries you receive about your research. To the extent possible, please include details regarding such as pertinent dates and names, titles, affiliations of people involved, etc.

## Research Brief

Please compose a research brief using the following template. To use the template, please replace all grey-highlighted text with the indicated desired content, and remove the highlight. Please use the font and page formatting set in the template. If you need to remove formatting from your text before copy-pasting into the template, you can paste into the Windows “text pad” program and recopy before pasting into the template.

Text for this brief should be accessible to professionals outside of academic institutions but within transportation fields.

If text does not fit within the allotted space and all for the 2-page format with the three subtitles per page, we will edit the text to fit.

For assistance or clarifications, please contact either of the following STC staff:

Susan Handy, Director
slhandy@ucdavis.edu

Mary Madison Campbell, Research Reporting Coordinator
memadison@ucdavis.edu

UCDAVIS
SUSTAINABLE TRANSPORTATION CENTER
of the Institute of Transportation Studies

**RESEARCH BRIEF**
Research Project: **DG 06-7**
09/2006 – 09/2007
Total Award: $30802

# STOCHASTIC MODELS FOR TRANSPORTATION NETWORK PROTECTION

PI: Changzheng Liu, Civil and Environmental Engineering (czliu@ucdavis.edu)

## ISSUE

Transportation infrastructure networks are under risk of nature disasters such as earthquakes. Pre-disaster retrofit has proved to be one of effective measures to enhance system resilience and thus mitigate disaster loss. This research studies the problem of allocating limited retrofit resources to competing network components given budget constraints. A specific form of research questions is which bridges (or tunnels) should be retrofitted subject to budget limitation in order to minimize disaster loss.

Current practice of prioritizing retrofit activities is to rank facilities according to their importance (e.g. measured by daily traffic volume carried by facilities) and vulnerability under seismic hazard. This ranking method fails to consider interdependency among network components and disaster uncertainty. The goal of this research is to develop a rigorous methodology that optimizes the allocation of retrofit resources to most critical transportation facilities.

## KEY FINDINGS

An optimal solution resulting from low budget may not necessarily be a subset of an optimal solution from high budget, which indicates that retrofit decisions based on simple engineering ranking approaches may be questionable.

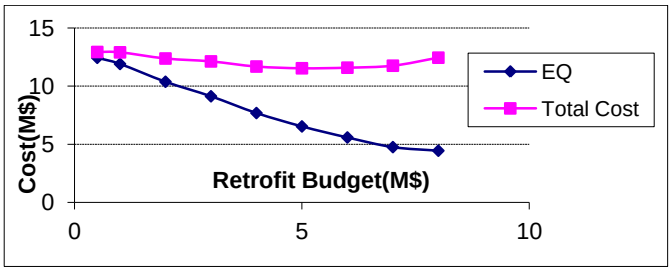


Figure 1: Retrofit Budget Vs. System Cost

A retrofit program may bring positive impacts to society. Apparently, there is a tradeoff between the retrofit investment and system cost. As plotted in Figure 1, the expected system cost EQ (including repairing cost and travel delay cost) decreases as more retrofit funding is invested. As more retrofit funds become available, the total cost (retrofit cost plus the expected system cost) also decreases until a certain point (5M$ in this case) is reached. For example, as the retrofit budget increases from 0.5M$ to 4M$, the total system cost decreases from 12.9M$ to 11.7M$. The gained benefit is about 10%.

Our model provides retrofit strategies is both efficient (by minimizing expected system cost) and robust (performing relative well under each hazard scenario).

## POLICY IMPLICATIONS

Current Practice of prioritizing retrofit activities could be greatly improved by incorporating research findings from this research. The developed methodology is mathematically rigorous, identifying critical facilities from the system level in consideration of probability distribution of seismic hazards.

## METHODOLOGY

Stochastic models are developed based on stochastic programming and network theory, which explicitly captures network interdependency and hedges against disaster uncertainty. Efficient algorithms are designed and implemented to solve these models. Two variants of the network retrofit problem were studied. Firstly assuming network flows are completely controllable to achieve system optimum (SO), the problem is formulated as a two-stage risk averse stochastic program with nonlinear recourse and binary variables in the first stage, which seeks a balance between minimizing expected system cost and reducing system cost variation. An efficient algorithm is designed via extending the well-known L-shaped method. Numerical experiment results demonstrate the superiority of the stochastic programming approach to the engineering method. Secondly assuming network flows are in the user equilibrium (UE) condition, the problem is formulated as a stochastic mathematical program with complementarity constraints (SMPCC), which is hard to solve due to its non-convexity and non-smoothness. The Progressive Hedging (PH) method is employed to solve the SMPCC, which iterates between the process of solving scenario (perturbed) subproblems and aggregating scenario solutions into an implementable policy. Each scenario subproblem, a mathematical program with complementarity constraints (MPCC), is solved via a relaxation approach.

## RESULTS

Compared with other simpler methods including engineering method in practice and scenario analysis method, the developed SP method provides the solution with minimum expected system cost. Moreover, the developed method is also robust and reliable, which is illustrated by figure 1, the cumulative distribution of system cost under different solutions. For example, at 80% reliability level, the SP solution produces a cost threshold of 10M$, but the engineering method solution produces a higher threshold of 14M$.

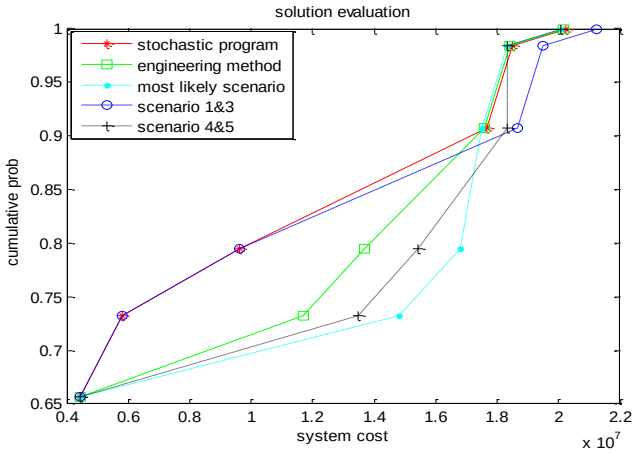


Figure 1: Reliability Evaluations of Different Retrofit Solutions

## PUBLICATIONS & PRESENTATIONS


Fan, Y. and C. Liu, R. Lee, and A. Kiremidjian (2010) Highway Network Retrofit under Seismic Hazard, Journal of Infrastructure Systems Vol. 16(3), pp. 181-187.

Liu, C., Y. Fan, and F. Ordonez (2009) A Two Stage Stochastic Programming Model for Transportation Network Protection, Computers and Operations Research, Vol. 36(5) pp. 1582-1590.

Fan, Y. and C. Liu (2009) Solving Stochastic Transportation Network Protection Problems Using the Progressive Hedging-based Method, Networks and Spatial Economics, vol. 10(2), pp. 193-208.

Liu, C. (2009) Transportation Networks Protection under seismic hazards", the Sixth International Conference on Urban Earthquake Engineering, Tokyo, Japan, March 2009

Fan, Y. and C. Liu (2008) "Effects of Risk Preferences on Network Design Decision", Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting, Washington, DC, USA, October 2008.

Liu, C. and Y. Fan (2008) "Solving the Highway network retrofit problem, the 10th International Conference on Application of Advanced Technologies in Transportation", Athens, Greece, May 2008.

Liu, C. and Y. Fan (2007) "A Two-stage Stochastic Programming Model for Transportation Network Retrofit", the 86th Transportation Research Board (TRB) Annual Meeting, Washington, DC, USA, January 2007.

Liu, C. and Y. Fan (2007) "Numerical methods for solving stochastic programming with equilibrium constraints", Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting, Seattle, USA, November 2007.
Liu, C. and Y. Fan (2007) "Stochastic Transportation Network Retrofit", Institute for Operations Research and the Management Sciences (INFORMS) Annual Meeting, Pittsburgh, USA, November 2006.

## NEW RESEARCH DIRECTIONS

One immediate extension of this research is to retrieve general policy guidelines from stochastic programming solutions. More specifically, we want to further explore the space of optimal solutions and found out the associations between optimal retrofit strategy and the features of network links under hazards. These features can be summarized as rules to guide retrofit practice. Another extension is to investigate the impact of different risk preferences on solutions. Decision makers' attitude toward risks could vary from risk-neutrality to different extent of risk-aversion. Understanding how decision makers' risk preferences might affect their choices and eventually impact the effectiveness of the entire society will have significant policy implications.

In general this research, with the successful application of stochastic programming in transportation network protection, fills the gap in the literature body of critical infrastructure protection and disaster prevention. It is our hope that this work will attract more research effort into this important field.

*Find out more about the UC Davis Sustainable Transportation Center at http://stc.ucdavis.edu*

*The research was supported by a grant from the Sustainable Transportation Center at the University of California Davis, which receives funding from the U.S. Department of Transportation and Caltrans, the California Department of Transportation, through the University Transportation Centers program.*

## Final Product

**You are required to submit a final product for your project.** This product will usually be in the form of a research report published through the ITS on-line database. Peer-review publications can be posted in lieu of a research report, provided they demonstrate equivalent documentation of the project. In either case, the official STC acknowledgement must be included, and research reports should also include the official disclaimer, both provided below. For some projects, other types of products (e.g. CD-ROM, website) might be appropriate.

Research reports should give a complete description of the problem, approach, methodology, findings, conclusions, recommendations, etc., developed in the project and completely documents all data gathered, analyses performed, and results achieved.

Examples of Final Research Reports can be found at the following two URLs (not from the STC, but from other University Transportation Centers in California, subject to the same reporting requirements):

*http://stc.ucdavis.edu/DOCS/FinalRep_Samples/MET_06-10_Final_Report.pdf*
*http://stc.ucdavis.edu/DOCS/FinalRep_Samples/MTI_Equity_Analysis_of_Land_Use.pdf*

Please use a front cover that looks like the template on the following page (feel free to copy-paste within bracketed text.)

Please include a table of contents, list of tables, and list of figures showing corresponding page numbers.

All reports and papers should include the following acknowledgement:

> **ACKNOWLEDGEMENT**
> The research was supported by a grant from the Sustainable Transportation Center at the University of California Davis, which receives funding from the U.S. Department of Transportation and Caltrans, the California Department of Transportation, through the University Transportation Centers program.

The inside of the front cover of the research report must show a disclaimer including the following:

> **DISCLAIMER**
> The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of the Department of Transportation University Transportation Centers Program, in the interest of information exchange. The U.S. Government assumes no liability for the contents or use thereof.

UCDAVIS
SUSTAINABLE TRANSPORTATION CENTER
*of the Institute of Transportation Studies*

Final Research Report [project number]

# [Report Title: Subtitle]

[month year]

[List of full names of all authors,
Each name on a separate line.]

Department of [Home Department of Corresponding Author]
University of California, Davis
One Shields Ave., Davis, CA 95616