On a semi-annual basis the NTC sponsored P.I. must report Program Progress Performance Report (PPPR) using the format specified in this PPPR Information Form. The form must be submitted electronically to the corresponding NTC Associate Director by 2/22/2016.


<table>
<thead>
<tr>
<th>NTC Funded Project Information (Round/Year 2, 2014-2015)</th>
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<tbody>
<tr>
<td><strong>University Name</strong></td>
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<td><strong>Project Title</strong></td>
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<tr>
<td><strong>Principal Investigator</strong></td>
</tr>
<tr>
<td><strong>PI Contact Information</strong></td>
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The form includes the following six parts:

- Part I – Performance Indicators
- Part II – Accomplishments: What was done? What was learned?
- Part III – Products: What has the program produced?
- Part IV – Participants & Collaborating Organizations: Who has been involved?
- Part V – Impact: What is the impact of the program? How has it contributed to transportation education, research and technology transfer?
- Part VI – Changes/Problems

*Supplementary documents/materials can be attached to this form with the submission.*
# Part I – Performance Indicators

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<tr>
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1. **Transportation-related courses offered during the reporting period that were taught by faculty and/or teaching assistants who are associated with the UTC**

   **Undergraduate courses**

   **Graduate courses**

   - ENCE 677
     - OR Models for Transportation Systems Analysis, University of Maryland
   - ENCE 688T
     - Transportation Network Algorithms and Implementations, University of Maryland

2. **Students supported by this grant**

   **Undergraduate students**

   **Masters students**

   **Doctoral students**

   - Hossein Fotouhi (with fellowship)
   - Neza Vodopivec
   - Seksun Moryadee (working on this award and another)

3. **Students participating in transportation research projects funded by this grant (but not supported by this grant)**

   **Undergraduate students**

   **Graduate students**

4. **Students supported by this grant who received degrees**

   **Undergraduate degrees**

   [Student Name]
Part II – Accomplishments: What was done? What was learned?

The information provided in this section allows the OST-R grants official to assess whether satisfactory progress has been made during the reporting period.

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1. What are the major goals of the program?

The National UTC aims to promote strategic transportation policies, investment, and decisions that bring lasting and equitable economic benefits to the U.S. and its citizens. The Center is concerned with the integrated operations and planning of all modes serving the nation’s passenger and freight transportation system, including the institutional issues associated with their management and investments. A balanced multi-modal approach will be used that considers freight and passenger travel mobility, reliability, and sustainability, as well as system operations during periods of both recurring and non-recurring incidents, including response to major emergencies. The modes in this theme include highway, transit, rail, and inter-modal interfaces including ports, terminals and airports. In particular, the center focuses on research, education, and technology transfer activities that can lead to (1) Freight efficiency for domestic shipping and for our international land, air, and sea ports; (2) Highway congestion mitigation with multi-modal strategies; and (3) Smart investments in intercity passenger travel facilities such as high speed rail. Major center activities are as following:

- **Advanced & Applied Research Promoting Economic Competitiveness:**
  Our research activities are multimodal/intermodal and multidisciplinary in scope, with the aims of addressing nationally and regionally significant transportation issues pertinent to economic competitiveness and providing practice-ready solutions.

- **Education, Workforce Development, Technology Transfer, & Diversity**
  The consortium is committed to providing high-quality transportation education and workforce development programs for a broad and diverse audience. Center’s efforts will support the
Development of a critical transportation knowledge base and a transportation workforce that is prepared to design, deploy, operate, and maintain the complex transportation systems of the future.

<table>
<thead>
<tr>
<th>2. What was accomplished under these goals?</th>
<th><strong>Project:</strong> A System-of-Systems Approach to Creating Resilient Transportation Systems given Interdependencies with Other Critical Lifelines <em>(PI: Miller-Hooks)</em></th>
</tr>
</thead>
<tbody>
<tr>
<td>Task 1. Literature review with emphasis on modeling failures and failure mechanisms, network modeling approaches to dynamically evolving topologies, and specifics of interdependencies between lifelines with particular relevance to the transportation system (95% complete).</td>
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</table>

The literature has been scoured for applications involving interdependencies between transportation systems and other critical lifelines. The interdependencies and how they arise in the context of transportation have been categorized and tabulated. Study of failure mechanisms arising from interdependencies with power networks are under study. The impact of disaster events on power and transportation networks individually has also been investigated. Feasible preparedness and response actions associated with power restoration related to disaster events as required for the operation of various transportation services have been examined.

The literature survey revealed two primary approaches to studying interdependencies: empirical and predictive approaches. In the former, two main sources are utilized: previous data and expert judgment. Previous data are collected from previously occurring extreme events. Interactions between lifelines are often determined through interviews of infrastructure managers and operators. Predictive approaches focus on modeling interdependencies for the purpose of gaining insights. In this category, the most relevant papers to our work are those in which network flow models have been utilized. In this type of modeling approach, each infrastructure is modeled as a network with multiple flow commodities (e.g. power in megawatts and cars) in which providing end users
The objective is to minimize the weighted unmet demand across the infrastructures given their interdependencies.

Most relevant works provide results from specific assessments, allowing for evaluation of the system in its current state. The models do not discuss investments in mitigation, preparedness or response that can improve system performance. That is, they are descriptive rather than normative. In the context of transportation systems resilience, however, a mathematical modeling approach which seeks to maximize the resilience of the transportation network by considering mitigative or preparedness actions (pre-event actions), as well as repair actions (post-event actions) is needed to capture the relevant interactions between transportation and other lifelines. This created the need for precise understanding of interdependencies between transportation systems with other lifelines at component level.

**Task 2.** Develop a mathematical model(s) of the transportation system as part of a system of systems with dynamically evolving network topology. Explore techniques and insights gleaned from system of systems methods, natural systems modeling, dynamic network flows, social networks, and other relevant areas (50% complete).

We have developed a static model for resilience quantification that includes decision variables for selecting preparedness and response actions given a limited budget to be applied over a coupled electric power and traffic network. Coupling of the models is accomplished through logical constraints. Within the model, the disaster event can affect either the powerlines and/or substations within the power network and/or the signals and links of the traffic network. While keeping to a budget, preparedness and response actions in either network are contemplated with the goal of maximizing resilience of the transportation network. Resilience is measured as the ratio of pre-event to post-event total link travel time. Post-event performance is considered for the disaster’s immediate aftermath.

We have formulated the problem of measuring and
maximizing traffic network resilience given interdependencies with the power network as a bi-level, stochastic, mixed integer, nonlinear program. Interdependencies between traffic and power networks are modeled by incorporated linking constraints within the mathematical model. Scenarios involving damage to all substations within the power network and signals and roadway links within the traffic network were created and tested. Interdependencies that arise between power and traffic as a consequence of imbalances in demand on the power network and power network repairs required post-damage event that use the transportation links have been studied and modeled. The model has been implemented in GAMS for a section of downtown Minneapolis involving the coupling of the traffic and power networks. The network involves multiple substations and feeders with transmission lines. A linearized DC power modeling method for power flow was incorporated. Linearization techniques have been applied for solution of this more realistic problem. Work continues on modeling system dynamics.

**Task 3.** Assess transportation network vulnerabilities from damage or major disruption within the transportation system itself or its interconnected lifelines using such techniques as node/arc removal, simulation, and case study or empirical analysis for multiple hazard scenarios.

A bi-level, stochastic, mixed-integer, nonlinear program with coupling constraints was developed to model coupled power and traffic networks. A case study of a portion of Minneapolis was created, and a variety of tests were conducted. The tests aided in assessing the logic of the developed mathematical model. These tests have led to new insights in terms of the mechanisms by which taking appropriate actions within the power network after a disruption event can benefit the traffic network through congestion relief and vice versa in terms of effect on repair actions to the power network. Taking some planned recovery actions to damaged substations may not be possible because the paths to those substations may be blocked due to link closures in the traffic network. Consequently, by appropriately modeling the interdependencies between power-network repair operations and traffic network state, their
impact, along with actions taken to address failures that occur due to these interdependencies, on transportation resilience have been quantified for the case system of systems.

**Task 4.** Explore the effectiveness of potential actions that can be taken to make transportation infrastructure more resilient given interdependencies with other systems. Seek answers to the following types of questions: Which lifelines are most critical for transportation system functioning? What are the origins of propagating failures? Which lifelines should be strengthened and what is the effect of such actions on transportation system performance? Is it more effective to strengthen other lifelines rather than transportation infrastructure directly? (100%)

The electric power-traffic network model developed in this study was used to investigate the impact on travel times of investments in preparedness and recovery actions to either or both traffic and power networks. The results of the runs on four disaster scenarios illustrate trade-offs between taking preparedness and recovery actions and across traffic and power networks. This results also showed the value of choosing between investment alternatives across lifelines. Specifically, the results showed that with higher budget available to invest on both transportation and power network, the resilience increases. However, the performance of the power network in terms of unmet demand does not necessarily improve for greater available budget. Furthermore, when the budget is limited to only one network, even greater benefits were noted from investing in the transportation components of the coupled system than in the components of the power network.

The results from the case study also showed that of all damage types considered in the scenarios, damage to traffic signals have the greatest impact on total post-event travel times. Damage to roadway links can also increase the total travel time post event, but has less impact than damage to the signals. Damage to elements of the power network results in higher travel times but with smaller impact compared to damage to traffic signals and links. This has implications for repair
Task 5. Develop the conceptual framework, related mathematical modeling and solution techniques needed for resilience quantification (100%).

A bi-level, stochastic mixed-integer, nonlinear program was developed that seeks the set of preparedness and response actions to minimize total travel time across the traffic system and thus maximize resilience. Any disruption is realized through its creation of additional delay for drivers. First-stage decision variables are a set of preparedness/mitigative actions. The purpose of these actions is to mitigate the effects of future failures under one or more of a set of potential disaster/disruption scenarios. These actions also aid in reducing the cost and enabling recovery actions in response to a specific event. The dependencies between power and transportation network are modeled through two-way connections between substations and traffic signals (or power lines that serve transit lines). These constraints have been developed, implemented and tested for a small problem network as mentioned above.

The proposed model falls within the class of non-convex optimization problems. We have discovered that solution of this non-convex problem even for small problem instances requires enormous computational effort. Moreover, a globally optimal solution may not be guaranteed using most of commercial solvers. Significant effort was given to linearizing the model. Methods of linearization from the literature have been implemented and tested.

A single-level equivalent formulation that exploits a proof of optimality from the literature related to equivalent Karush Kuhn Tucker (KKT) conditions was developed. The extensive form of this model was coded in GAMS.

For larger problem instances, an alternative approach solution method is required. Decomposition approaches have been explored and implemented. Two approaches were explored: decomposition by time stage (Benders or integer L-shaped) and by scenario (a dual decomposition method combined with
Lagrangian relaxation).

**Task 6.** Apply developed concepts and techniques on an illustrative example network. Evaluate the importance of explicitly accounting for interdependencies in resilience quantification in the study context (100%).

Runs conducted on the case study mentioned in relation to prior tasks sought resilience estimates by: budget level, performance of the coupled system wherein expenditures are limited to only one network, and performance under restricted repair situations. Both traffic and power network performance were studied.

Task 7. Disseminate knowledge gained through the proposed research effort through publications in journals/proceedings, in presentations at conferences or in invited lectures and in a final report. Complete additional interim reports as desired by the funding agency.

**Lectures:**


**Articles:**


**3. How have the results been disseminated?**

[Describe how the results have been disseminated. Include any outreach activities that have been undertaken to reach members of communities who are not usually aware of these program activities, for the purpose of enhancing public understanding and increasing]
interest in learning and transportation careers.

See Task 6 above.

| 4. What do you plan to do during the next reporting period to accomplish the goals? (10/1/2014 – 3/10/2016) | • Implement the developed decomposition method for larger numbers of scenarios and compare its performance to that of the extensive form with the GAMS solver.
• Develop conceptual framework and approach for dealing with problem dynamics. |

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<tr>
<th>Part II – Products: What has the program produced?</th>
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<tr>
<td>Publications are the characteristic product of research projects funded by the UTC Program. OST-R may evaluate what the publications demonstrate about the excellence and significance of the research and the efficacy with which the results are being communicated to colleagues, potential users, and the public, not the number of publications. Many research projects (though not all) develop significant products other than publications. OST-R may assess and report both publications and other products to Congress, communities of interest, and the public.</td>
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<tr>
<th>2. Books or other non-periodical, one-time publications</th>
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<tr>
<td>[Report any book, monograph, dissertation, abstract, or the like published as or in a separate publication, rather than a periodical or series. Include any significant publication in the proceedings of a one-time conference or in the report of a one-time study, commission, or the like.]</td>
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</table>

[Identify for each one-time publication: Author(s); title; editor; title of collection, if applicable; bibliographic information; year; type of publication (book, thesis or dissertation, other); status of publication (published; accepted, awaiting publication; submitted, under review; other); acknowledgement of federal support (yes/no).]


| 4. Website(s) or other Internet site(s) | http://www.millerhooks.umd.edu/projects/proj47.html |
| 5. Technologies or techniques | [Identify technologies or techniques that have resulted from the research activities. Describe the technologies or techniques and how they are being shared. Such as Technologies or technology assessments] |
| 6. Outreach activities |  |
| 7. Courses and workshops |  |
| 8. Inventions, patent applications, and/or licenses | [Identify inventions, patent applications with date, and/or licenses that have resulted from the research. Submission of this information as part of an interim research performance progress report is not a substitute for any other invention reporting required under the terms and conditions of an award; as of the date of this document, UTC Program inventions may not be submitted to the Federal government’s Interagency Edison (iEdison) invention-reporting |
system, but OST-R is working to make that available and will notify UTCs. For additional requirements pertaining to Patents and Copyrights, refer to General Provisions of Grants for University Transportation Centers, Section III, 14.]

| 9. Other products | [Identify any other significant products that were developed under this program. Describe the product and how it is being shared. Examples of other products are:  
  • Databases  
  • Physical collections  
  • Audio or video products  
  • Software or NetWare  
  • Models  
  • Educational aids or curricula  
  • Instruments or equipment  
  • Data & Research Material  
  • Other] |

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**Part III – Participants & Collaborating Organizations: Who has been involved?**

OST-R needs to know who has worked on the project to gauge and report performance in promoting partnerships and collaborations.

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1. **What organizations have been involved as partners?**  
[Describe partner organizations – academic institutions, other nonprofits, industrial or commercial firms, state or local governments, schools or school systems, or other organizations (foreign or domestic) – that have been involved with the program.
Partner organizations may provide financial or in-kind support, supply facilities or equipment, collaborate in the research, exchange personnel, or otherwise contribute.

[Provide the following information for each partnership:
Organization Name:
Location of Organization: (if foreign location list country)
Partner’s contribution to the project (identify one or more)
• Financial support;
• In-kind support (e.g., partner makes software, computers, equipment, etc., available
• to project staff);
• Facilities (e.g., project staff use the partner’s facilities for project activities);
• Collaborative research (e.g., partner’s staff work with project staff on the project); and
• Personnel exchanges (e.g., project staff and/or partner’s staff use each other’s
• facilities, work at each other’s site).]

| 2. Have other collaborators or contacts been involved? | We have talked with Dr. Jeremy Lin, a senior engineer at PJM Interconnection. He has answered our questions about concepts of direct current (DC) power modeling and power system restoration under natural disasters. PJM is a regional transmission organization that coordinates the movement of wholesale electricity in all or parts of Delaware, Illinois, Indiana, Kentucky, Maryland, Michigan, New Jersey, North Carolina, Ohio, Pennsylvania, Tennessee, Virginia, West Virginia and the District of Columbia. |

Part IV – Impact: What is the impact of the program? How has it contributed to transportation education, research and technology transfer?

DOT uses this information to assess how the research and education programs:
• increase the body of knowledge and techniques;
• enlarge the pool of people trained to develop that knowledge and techniques or
• put it to use; and,
• improve the physical, institutional, and information resources that enable those people to get their training and perform their functions.

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<tbody>
<tr>
<td><strong>1. What is the impact on the development of the principal discipline(s) of the program?</strong></td>
<td>Successful completion of this interdependency modeling work will aid governments and infrastructure owners and operators in creating more resilient transportation infrastructure systems. Insights gained and mathematical techniques developed through this work will inform these entities on the optimal investment of limited funds across critical lifelines, subsystems, and system components.</td>
</tr>
<tr>
<td><strong>2. What is the impact on other disciplines?</strong></td>
<td>[Describe how the findings, results, or techniques developed or improved, or other products from the program made an impact or are likely to make an impact on other disciplines.]</td>
</tr>
</tbody>
</table>
| **3. What is the impact on the development of transportation workforce development?** | [Describe how the program made an impact or is likely to make an impact on transportation workforce development. For example, how has the program:

  • Provided opportunities for research and teaching in transportation and related disciplines;
  • Improved the performance, skills, or attitudes of members of underrepresented groups that will improve their access to or retention in transportation research, teaching, or other related professions;
  • Developed and disseminated new educational materials or provided scholarships; or provided exposure to transportation, science and technology for practitioners, teachers, young people, or other members of the public?] |
| 4. What is the impact on physical, institutional, and information resources at the university or other partner institutions? | (Describe ways, if any, in which the program made an impact, or is likely to make an impact, on physical, institutional, and information resources that form infrastructure, including:

- Physical resources such as facilities, laboratories, or instruments;
- Institutional resources (such as establishment or sustenance of societies or organizations);
  or
- Information resources, electronic means for accessing such resources or for scientific communication, or the like.) |
|---|---|
| 5. What is the impact on technology transfer? | (Describe ways in which the program made an impact, or is likely to make an impact, on commercial technology or public use, including:

- Transfer of results to entities in government or industry;
- Instances where the research has led to the initiation of a start-up company; or
- Adoption of new practices.) |
| 6. What is the impact on society beyond science and technology? | A transportation network is a critical lifeline for a community, essential to the functioning of society and the viability of the economy. The wellbeing of the community’s members depends on their mobility, ability to move goods, and access to services. In disaster situations, a well-operating transportation system is crucial to search and rescue efforts, accessibility of emergency personnel, evacuation and sheltering, distribution of essential supplies, and ability to respond quickly to acute medical needs. After a disaster, a functioning transportation network allows a community to repair damaged infrastructures and recover economically. Thus, having a resilient transportation infrastructure system that performs well under multiple hazards...
situations is critical to a community.

This research effort investigates the role of these interdependencies in transportation system resilience, and develops quantitative resilience quantification tools that account for the impact that arises from these interdependencies on resilience level. These insights and tools will support government agencies and transportation and other critical infrastructure owners and operators in making optimal investments and in optimally preparing for disaster events whether natural or malicious.

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<th>7. Additional impacts</th>
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<tr>
<td>[NTC encourages to consider identifying program results by outcomes or impacts, as suggested by the examples below. Impacts should be linked to National goals expressed in the Secretary’s Strategic Goals.]</td>
</tr>
</tbody>
</table>

[Outcomes are broader changes that are expected to result from the products, such as:
• Increased understanding and awareness of transportation issues;
• Improved body of knowledge;
• Improved processes, techniques and skills in addressing transportation issues;
• Enlarged pool of trained transportation professionals;
• Greater adoption of new technology;
• Other impacts.]

Impacts are the longer-term, fundamental changes intended as a result of your activities, such as:
• Safer driver behavior;
• Increased travel time reliability;
• Increased intermodal transportation operations;
• Reduction in carbon and other harmful emissions from transportation sources;
• Other impacts. ]
### Part V – Changes/Problems

If not previously reported in writing to OST-R through other mechanisms, provide the following additional information or state, “Nothing to Report, if applicable:

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<tr>
<th>Reporting Period</th>
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<tbody>
<tr>
<td><strong>1. Changes in approach and reasons for change</strong></td>
<td>[If there is nothing significant to report during this reporting period, state “Nothing to Report.”]</td>
</tr>
<tr>
<td></td>
<td>[Describe any changes in approach during the reporting period and reasons for these changes. Remember that significant changes in objectives and scope require prior approval of the OST-R grant administrator.]</td>
</tr>
<tr>
<td><strong>2. Actual or anticipated problems or delays and actions or plans to resolve them</strong></td>
<td>[If there is nothing significant to report during this reporting period, state “Nothing to Report.”]</td>
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<tr>
<td></td>
<td>[Describe problems or delays encountered during the reporting period and actions or plans to resolve them.]</td>
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<tr>
<td><strong>3. Changes that have a significant impact on expenditures</strong></td>
<td>[If there is nothing significant to report during this reporting period, state “Nothing to Report.”]</td>
</tr>
<tr>
<td></td>
<td>[Describe changes during the reporting period that may have a significant impact on expenditures, for example, delays in hiring staff or favorable developments that enable meeting objectives at less cost than anticipated.]</td>
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</tbody>
</table>
| **4. Significant changes in use or care of human subjects, vertebrate animals, and/or biohazards** | [If there is nothing significant to report during this reporting period, state “Nothing to Report.”]

[Describe significant deviations, unexpected outcomes, or changes in approved protocols for the use or care of human subjects, vertebrate animals, and/or biohazards during the reporting period. If required, were these changes approved by the applicable institution committee and reported to the agency? Also specify the applicable Institutional Review Board/Institutional Animal Care and Use Committee approval dates.] |
| **5. Change of primary performance site location from that originally proposed** | [If there is nothing significant to report during this reporting period, state “Nothing to Report.”]

[Identify any change to the primary performance site location identified in the proposal, as originally submitted.] |