Prioritization of Schedule Dependencies in Hurricane Recovery of Transportation Agency

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Abstract: A transportation agency must consider the efficiency of its hurricane preparedness, response, and recovery operations. This paper develops and demonstrates a methodology to identify and characterize the schedule dependencies and subsequent delays that arise among federal, state, and local agencies and organizations involved in the pre and posthurricane processes in order to reduce the time for a region to recover from a natural disaster. The large scale of an agency's overall recovery from a natural disaster presents a challenge to conventional scheduling models, including program evaluation and review technique and critical-path methods. A metanalysis to support agency resource allocation is thus developed as follows. Instances of schedule dependencies from past recoveries are collected and categorized according to the functional and organizational units of the agency. A categorical study is performed to highlight the functional units that are associated with the greater numbers of dependencies. The agency better understands which units need attention and which interfaces among units need improved coordination. The results of an example show that the interfaces of the *Information Management* unit and the *Operations* unit are sources of a significant portion of the dependency scenarios collected. The significance of the dependencies to the overall recovery is characterized in a multiattribute analysis. The analysis expresses the magnitude of a dependency in terms of its controllability, the involved agencies, resources involved, prevalence of similar scenarios, cascading effects, maturity, likelihood in the future, and severity in terms of its time duration. A transportation agency can use the developed methodology to identify, prioritize, and minimize the negative effects of schedule dependencies within and among agencies in recovery from a regionwide disaster. Recommendations are given to improve higher-level coordination both among the involved agencies and within the transportation agency.

DOI: 10.1061/(ASCE)1076-0342(2002)8:3(103)

CE Database keywords: Hurricanes; Transportation systems; Scheduling; Government agencies; Critical path method.

Introduction

Following a natural disaster, the communities in the affected region can be in an extreme state of disorder. The impacts can persist for months and years after the incident, influencing the economical and social well-being of the region. Because of the devastating consequences of delays, it is critical to maintain an adequate level of preparedness and planning to hasten the recovery. The current effort supports the recovery efficiency of a transportation agency that finds itself at the center of disaster preparedness and recovery operations. In a metanalysis of the schedule dependencies in the pre and postdisaster situations, a framework is developed for measuring, comparing, and categorizing schedule dependencies and subsequent delays that arise in the response activities following a regional natural disaster. The analysis identifies significant sources of schedule dependency and characterizes the significance of the dependencies to the overall recovery in order to suggest ways to minimize the time to full recovery. The developed methodology is applied to a sample of schedule dependency scenarios that were collected from agencies involved in past recoveries. The analysis identifies critical dependencies and inefficiencies within the transportation agency's divisions for further investigation. Recommendations are developed to lessen the impacts of controllable schedule dependencies in the recovery process.

The organization of this paper is as follows. The "Background" section provides a review of literature establishing the need for the current paper. The "Technical Approach" section develops a catalog of scenarios of schedule dependencies gathered from agencies in Virginia, California, Florida, North Carolina, and South Carolina from their participation in the preparedness, response, and recovery of past disasters. Situations are identified where a nontransportation agency depends or waits on the transportation agency and vice versa. The "Analysis of Results" section describes a categorical analysis of the collected scenarios according to the relevant individual and interfacing pairs of functional units involved within the transportation agency's organizational structure. The categorical analysis is used to highlight those units that are the source of many dependency scenarios. The section on "Measuring and Comparing Dependency Scenarios" develops a methodology for characterizing, measuring, and comparing dependency scenarios and demonstrates how to apply the methodology to an example scenarios. The conclusions section summarize the contributions of the paper, offers suggestions for further investigation, and provides recom-

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Note. Associate Editor: Samer Madanat. Discussion open until March 1, 2003. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on October 1, 2001; approved on May 6, 2002. This paper is part of the ***Journal of Infrastructure Systems***, Vol. 8, No. 3, September 1, 2002. ©ASCE, ISSN 1076-0342/2002/3-103–111/$8.00+$.50 per page.

J. Infrastruct. Syst., 2002, 8(3): 103-111

mendations for a transportation agency to make prehurricane investments of resources that could reduce the length of time of recovery in future disasters.

Background

Needs for improving natural disaster preparedness and recovery efforts have been addressed from various perspectives. Heaney et al. (2000) present the engineering research perspective for developing more sustainable natural disaster management. Heaney discusses lessons learned from past hurricanes and other natural hazards, and summarized the impacts of disasters on infrastructure including communications, bridges, and transportation systems. Higgins et al. (2000) examine the role of public transit agencies in extreme events and provided guidance for emergency management planning in coordination with the efforts of their local jurisdiction. Schiff (1995) summarizes the recovery of roads and bridges following the 1994 Northridge Earthquake in California, and discusses the impacts the destroyed road system had on other agencies involved in the disaster recovery. Recommendations for enhanced recovery plans and further research have been developed (Schiff 1995). Juhl (1993) discusses the collaboration of the Federal Emergency Management Agency (FEMA) and a software company to take steps to increase the efficiency of the pre and postdisaster processes by developing database applications using geographic information systems (GIS). Ardekani (1992) evaluates the response following the 1989 Loma Prieta Earthquake in California and provides recommendations for the preparedness of transportation agencies in the future. Ross (1988) identifies numerous effects natural disasters have on transportation systems.

The importance of systematic planning of the pre and postdisaster procedures has been recognized. Kovel (2000) discovered that the development of these preparation and recovery strategies is not given precedence over other tasks due to a lack of effective tools for use in the planning process. One tool to ensure an effective allocation of highway resources is a multiobjective analysis of the alternatives (Chowdhury et al. 2000). Gharaibeh and Darter (1999) developed a tool that could aid preparedness and recovery by prioritizing highway reconstruction activities. Boyd et al. (1998) describe the activities that are crucial for emergency management in transit to maintain adequate preparedness and recovery procedures. A design for evaluating the costs and benefits associated with preparedness activities was developed by Masri and Moore (1995). Tavano (1995) further discusses the necessary activities to perform in the preevent period to achieve a sufficient level of hurricane preparedness. Hancock et al. (1993) emphasize that the use of innovative techniques for emergency response planning is essential and identified the need for a systematic approach in evaluating the capabilities of agencies involved in disaster preparedness and recovery. Ullman et al. (1991) examine the roles of agencies involved with emergency traffic-management operations and highlight the importance of planning. Motivated by the need for a systematic study of the postdisaster process to improve emergency planning, Kozin and Zhou (1990) developed a formulation of lifeline-restoration processes during recovery.

Gunes and Korel (2000) explain the need for comprehensiveness in planning for the pre and postdisaster periods and find that emergency disaster management should not limit its focus to the direct, immediate effects of a natural disaster. Preparedness and recovery efforts become more beneficial when the complexity of managing these processes is realized (Gunes and Kovel 2000). Parentela and Nambisan (2000) stress that a prerequisite for the development and implementation of adequate emergency-response plans is an extensive range of information regarding factors and issues such as the environment, the capabilities of emergency-response providers, and the economy. Crichlow (1997) describes how recoveries from natural disasters are complex events.

Agency coordination before and after a natural disaster has been widely recognized as an important contribution to the efficiency of a recovery effort. Grajek and Gibson (2000) find that completion times of activities can be reduced with effective partnering and coordination of involved parties. Mondul (1997) stresses that information should be shared among agencies using the road system in the preparation and recovery processes. Kovel and Kangari (1995) find that a higher level of agency coordination would benefit these processes. Barnett (1987) explains that the procedures to follow during recovery should reflect statewide multiagency coordination and communication in terms of responsibilities, authority, and capabilities. The Transportation Research Board (1984) discusses the importance of identifying authority and communication channels among involved agencies and the private sector.

Schedule analysis has been examined by Peer (1974), McGough (1982), Bubshait and Cunningham (1998), Mullholland and Christian (1999), and Wang and Demsetz (2000). Babcock (1996) provides a range of network scheduling techniques and their applications including PERT and *critical path analysis* (CPA). Babcock states that the *critical path* of a sequence of events represents the longest path from one event to another. Babcock presents methods of formulating the time duration of a critical path of activities and demonstrates that the time to recovery can be reduced if the *critical path* of the recovery process is shortened. It is important to identify and minimize delays introduced by schedule dependencies among recovery activities that lie on the critical path. The importance of managing the potential risks to infrastructure including facilities that could suffer negative impacts from a natural disaster has been addressed by Ezell and Farr (2000), Haimes and Jiang (2001), and Hastak and Baim (2001). Hooke (2000) and Hecker et al. (2000) discussed the assessment of risk specifically associated with natural disasters. In addition, The Permanent International Association of Road Congresses (1999) developed methodologies incorporating risk management and emergency planning, and Housner and Chung (1997) provided evaluations of risk assessment and disaster recovery. Staneff et al. (1995) and Chang and Shinozuka (1996) describe that risks and impacts from natural disasters are important factors to be taken into account when determining the life cycle and management of infrastructure. Recovery scheduling has been considered in terms of managing activities of isolated reconstruction projects and has not been viewed comprehensively with attention to the complexity of a large-scale disaster recovery effort involving multiple agencies. The identified need can be summarized as an intersection of three issues/topics discussed as follows: (1) the need for effective disaster preparedness and recovery; (2) the adequacy of conventional schedule analysis including the formulation of the time duration of a critical path for isolated reconstruction activities; and (3) the inadequacy of tools for identifying, prioritizing, and reducing schedule risks in inter and intraagency coordination.

J. Infrastruct. Syst., 2002, 8(3): 103-111

Table 1. Descriptions and Categorization of Dependency Scenarios Collected; First Organizational Unit Listed for Each Scenario Represents Primary Contributor (in bold) to Dependency and Second Represents Secondary Contributor

Schedule dependency scenario (SD)	Description
SD06 bridge failure	The response of the local emergency medical services in the future to an isolated area could be delayed if there is a road or bridge failure that is waiting to be repaired by the state transportation agency.
SD07 available road status information	The local emergency medical services had to wait on the state transportation agency for the availability of current, updated road status information following a recent hurricane.
SD12 long-term road access	A local ambulance service is still experiencing delays from closed and almost nonaccessible roads due to flooding 2 years ago.
SD23 environmental violations	The environmental affairs unit of the state transportation agency has waited on the department of environment and natural resources for information regarding what recovery activities violate coastal development restrictions. Various repairs were delayed due to a lack of information regarding new environmental requirements. Some repairs were made before the state transportation agency was aware of the requirement changes.
SD29 fund reimbursements	The financial unit of the state transportation agency had to wait and is still waiting on FEMA and the Federal Highway Administration for fund reimbursements.
SD36 insufficient traffic management	Evacuation was delayed from insufficient traffic management resources, a lack of real-time road-condition information, and a lack of communication among surrounding states regarding traffic information. In particular, lane closures for work zones were reopened later than planned due to miscommunication.
SD42 restricted access	Personnel delays occurred because the state transportation agency emergency staffs identification badges only gave them access to their facilities during limited hours.
SD43 inconsistent barricades	The state transportation agency field units had to wait on the equipment unit for reinforcement barricades because suppliers sent barricade parts that were not standardized.
SD47 disposal sites	Because landfills and disposal sites had limited access and hours of operation, the state transportation agency field units experienced delays with debris removal.
SD48 processing reimbursements	The financial unit of the state transportation agency experienced delays for reimbursement even before submission to FEMA due to the extensive manual work involved with compiling the necessary documents.

Technical Approach

The overall recovery process following a regional natural disaster is on such a large scale that its representation as a holistic schedule network, linking all agencies, time domains, and geographic scales to identify a global critical path for recovery operations is not achievable. An approach is developed for identifying and prioritizing critical dependencies and functional units of the transportation agency. While it cannot be determined if the dependency scenarios collected lie on a global critical path of recovery, investigating and prioritizing dependencies can be undertaken so as to suggest that the global critical path will be shortened.

Data Collection

Data collected includes dependency scenarios from state and local agencies and organizations involved in disaster recovery. Dependency scenarios are collected through interviews of agencies regarding past recovery efforts. The interviews span Virginia, California, Florida, South Carolina, and North Carolina, focusing on their respective state transportation agencies. A particular dependency scenario could apply to a range of geographic scales such as a specific city intersection, a whole group of city blocks, or an entire county. A scenario could also exist on any time horizon ranging from the hours and days following the disaster in the

Schedule dependency #	Schedule dependency name	State	Agency name	Agency type	Level of agency	Pre/Post Disaster	Time horizon	Administration	Environ., Regulatory Affairs	Equipment	Finance	Information management	Legal/authorization	Materials	Operations	Personnel	Structure
SD06	Bridge Failure	VA	Office of Emerg. Med. Ser.	Health	State	Post	MT							○			●
SD07	Available Road-Status Info.	VA	Office of Emerg. Med. Serv.	Health	State	Post	ST					●		○			
SD12	Long-Term Road Access	CA	Hall Ambulances	Health	Loca	Post	LT							○			●
SD23	Environmental Violations	NC	Div. of Coastal Manage.	Envir.	State	Post	MT		○			●					
SD29	Fund Reimbursements	NC	FEMA	Emerg	State	Post	LT	○			●						
SD36	Insufficient Traffic Mgt.	NC	NC DOT	Trans.	State	Post	ST					●		○			
SD42	Restricted Access	NC	NC DOT	Trans.	State	Post	ST		●						○		
SD43	Inconsistent Barricades	NC	NC DOT	Trans.	State	Post	ST		○	●							
SD47	Disposal Sites	NC	NC DOT	Trans.	State	Post	MT		○								
SD48	Processing Reimbursements	NC	NC DOT	Trans.	State	Post	LT	○			●						

Fig. 1. Categorization of 10 collected dependency scenarios according to functional units involved within state transportation agency. Each row describes a dependency scenario. The *primary unit* involved is represented by a filled circle, and the *secondary unit* is represented by an unfilled circle. LT = long-term, etc.

J. Infrastruct. Syst., 2002, 8(3): 103-111

Table 2. Number and Percentage of Dependency Scenarios Collected that Are Associated with Each Functional Unit within State Transportation Agency

Unit type	Number of cases	Percent of total
Administration	3	6.2
Environmental, regulatory affairs	2	4.2
Equipment	4	8.3
Finance	2	4.2
Information management	15	31.3
Legal/authorization	2	4.2
Materials	2	4.2
Operations	11	22.9
Personnel	3	6.2
Structure	4	8.3
Total	48	100

short term to the months and years in the long term.

Approximately 500 agency representatives are contacted through phone interviews, e-mails, and facsimiles regarding the accounts they hold of past disaster recoveries. An example interview query asks "what is a case in which your agency has not been able to start a pre or postdisaster activity for which you are responsible because you were waiting on a transportation agency to complete a prerequisite task?" In addition to transportation agencies, the agencies interviewed include state police, health departments, environment, and emergency management among others.

Scenarios of schedule dependency are also identified from a report of the emergency-operations personnel of the North Carolina Department of Transportation (NCDOT) (2000), which is an evaluation of their response to a recent Category 2 hurricane. In particular, the report describes the effectiveness of their resource allocation, communications, and information management procedures following the recent hurricane, and discusses the intraagency dependencies they encountered caused by issues such as a lack of equipment standardization.

Over 200 dependency scenarios were collected. A sample of 10 dependency scenarios with their descriptions is given in Table 1.

Categorization of Dependency Scenarios

Dependency scenarios are classified according to the functional units or divisions of the state transportation agency's organizational structure. Two functional units have been determined and associated with each dependency scenario: One unit is the primary contributor and the other unit is the secondary contributor associated with the dependency. The categorization is useful to identify those units that are the source of the greatest number of dependencies in order to highlight areas needing further examination and planning by the agency. The following functional units are used to classify the dependency scenarios: (1) Administration, (2) Environmental, Planning, and Regulatory Affair, (3) Equipment, (4) Finance, (5) Information Management, (6) Legal/Authorization, (7) Materials, (8) Operations, (9) Personnel, and (10) Structure and Bridge.

The categories are self-explanatory with some additional clarifications. The *Information Management* unit, which functions to house and administer accurate information regarding road status, evacuations, environmental requirements, hazardous material, etc., is also responsible for the communication and availability of information to other agencies. The *Legal/Authorization* unit addresses obtaining environmental permits and granting authorization for other units and other agencies to access facilities and roads of the transportation agency. The *Operations* unit includes the responsibilities of all on-site field units and maintenance units. The *Structure and Bridge* unit functions to restore and reconstruct infrastructure such as roads, bridges, and tunnels (VDOT 1997).

A sample of the categorization of dependency scenarios is given in Fig. 1. Each row characterizes a different scenario of

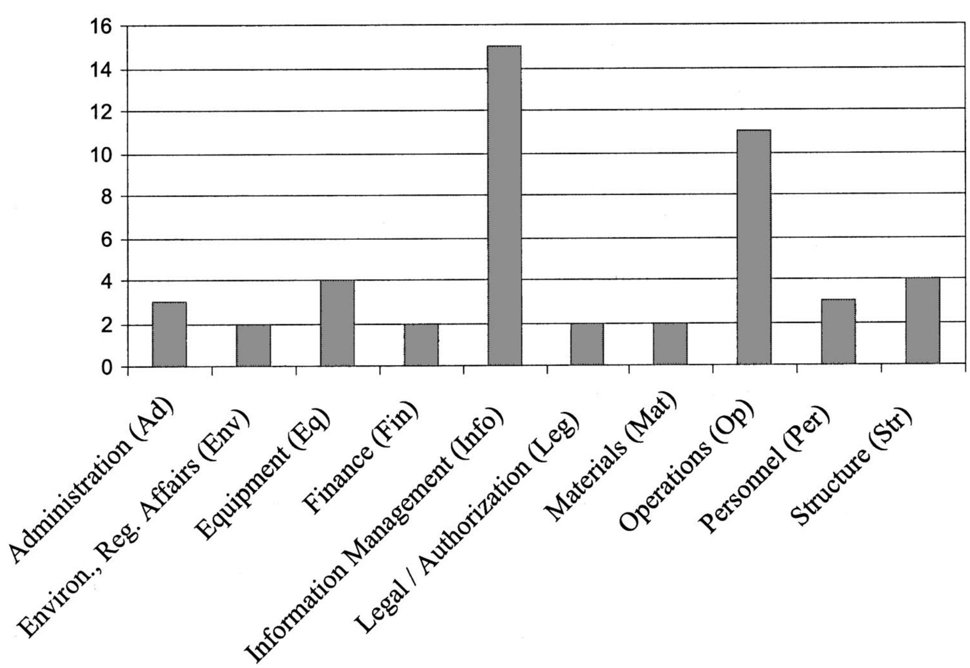

Fig. 2. Number of dependency scenarios that are associated with each individual functional unit within state transportation agency

J. Infrastruct. Syst., 2002, 8(3): 103-111

Table 3. Number and Percentage of Dependency Scenarios Collected that Are Associated with Each Pair of Functional Units within State Transportation Agency

Pairs of units	Number of cases	Percent of total
Information management-operations	11.0	22.0
Operations-structure	9.0	18.8
Environmental, regulatory affairs-information management	3.0	1.4
Environmental, regulatory affairs-operations	3.0	6.3
Equipment-information management	3.0	6.3
Information management-materials	2.0	4.2
Administration-personnel	2.0	4.2
Environmental, regulatory affairs-equipment	2.0	4.2
Environmental, regulatory affairs-personnel	2.0	4.2
Administration-information management	2.0	4.2
Administration-finance	2.0	4.2
Administration-operations	1.0	2.1
Environmental, regulatory affairs-legal/authorization	1.0	2.1
Equipment-legal/authorization	1.0	2.1
Information management-legal/authorization	1.0	2.1
Legal/authorization-operations	1.0	2.1
Materials-operations	1.0	2.1
Operations-personnel	1.0	2.1
Total	48	100

schedule dependency, and each column represents a different functional unit. Additional columns provide an index number and title associated with the dependency as well as the name, state, and type (communication, environmental, fire, health, military, police, transportation, utility) of the agency involved, the authority level of the agency (local, regional, state), the associated recovery-time horizon (short-term, medium-term, long-term), and whether the delay is associated with pre or postdisaster activities.

Analysis of Results

Analysis of Individual Organizational Units Involved

Using the categorization discussed in the Technical Approach Section, the dependency scenarios are first studied from the view of the primary functional units. The analysis identifies the organizational units that are the sources of a significant number of the dependencies in the sample collected across all states. As shown in Table 2, and the corresponding bar graph in Fig. 2, the *Environmental and Regulatory Affairs*, *Finance*, *Legal/Authorization*, and *Materials* units are associated with few dependencies, each accounting for only 4.2% of all scenarios collected. Nearly 23% of all dependencies collected are primarily involved with the *Operations* unit, and over 30% are involved with the *Information Management* unit. The results of the analysis alert the transportation agency to review the recovery planning involving the *Information Management* division.

Review of the dependency scenarios collected shows that many of interviewed agencies waited on a transportation agency for current and accurate road-condition information. Other information that was not available to agencies that subsequently caused delays includes the locations of hazardous materials to guarantee the safety of field forces, the current locations of floodplains, the requirements for environmental permits, and the actions constituting environmental violations.

Analysis of Organizational Unit Interaction

A dependency can arise from the interaction of two or more functional units of the transportation agency, because of this, a similar analysis has been performed of the *pairs* of units involved in each dependency. The analysis highlights the pairs of functional units that are involved with a significant amount of dependencies (Lambert et al. 2001), and the transportation agency can use the results to learn which units need to be more efficiently coordinated.

Table 3 shows the number of dependency scenarios associated with pairs of associated functional units. Out of the 45 possible pairs of organizational units, only 18 pairs are associated with at least one delay scenario. As shown in Table 3 and the corresponding bar graph in Fig. 3, the interaction of the *Information Management* and *Operations* units and the interaction of the *Opera-*

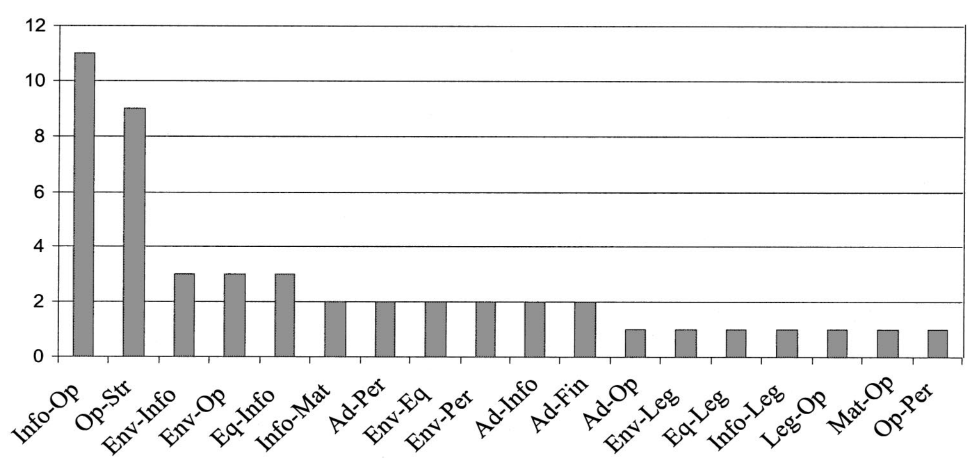

Fig. 3. Number of dependency scenarios collected that are associated with each pair of functional units within state transportation agency

J. Infrastruct. Syst., 2002, 8(3): 103-111

Table 4. Measure of Severity using Time Horizon in Order to Measure Importance of Dependency Scenario

Length of time of delay	Horizon		
	Short term	Medium term	Long term
Hours	Moderate	Low	Low
Days	High	Moderate	Low
Weeks	High	High	Moderate
Months	High	High	High
Years	High	High	High

tions and *Structure and Bridge* units both are involved in a large number of delays, accounting for 23 and 19% of the total sample respectively.

One way to improve the coordination between the *Operations* and *Structure and Bridge* units, which are both primarily made up of field personnel working on site, is to provide truck-to-truck communication possibly via cellular phones (NCDOT 2000). Another way to improve coordination among the *Operations*, *Structure and Bridge*, and *Information Management* units is through the implementation of a common statewide radio system for involved agencies, which also provides a secure means of backup for the real-time information system discussed earlier. A radio system with the required frequencies decided in the predisaster phase supports an effective evacuation and curtails the time wasted locating necessary radio equipment for responding to emergency personnel, which was a delay suffered by the NCDOT following a recent hurricane (NCDOT 2000).

Additional Potential Dependencies and Possible Resolutions

Often during hurricane recovery, personnel from unaffected regions relocate to provide assistance to areas in need (Susan Toth, personal communication, October, 2000). In addition, spare equipment is often shipped to the areas in need from other regions. It is important for all relevant transportation-agency employees to be able to operate all equipment used during the recovery process regardless of its source. This problem arose during hurricane recovery efforts of the NCDOT. Their recovery activities were delayed because various pieces of equipment were not operable by transferred personnel who lacked the necessary training (NCDOT 2000). In order to prevent this setback in the future, equipment likely to be used during the postdisaster process should be standardized across the state, and relevant personnel should receive the appropriate training required for use.

In order to optimize the deployment of equipment and materials that are frequently shipped around a region during recovery, it is necessary to ensure their packaging allows for easy transport. One way to potentially speed the time to recovery is to prepackage those resources likely to be needed in postdisaster procedures, which can be determined by reviewing past equipment request orders (NCDOT 2000).

Personnel coming to help from regions that escaped the natural disaster may be unfamiliar with certain procedures and information that are specific to the transportation agency residencies in need. Dependencies can arise while the relocated workers learn how to follow and become acquainted with these new processes and methods (NCDOT 2000). Though personnel from across the state need not know all information about the area they are assisting, such as the local topography, it is necessary for them to be trained and competent with the equipment, materials, and internal operations employed by the units involved (NCDOT 2000). Assigning ‘‘partner residencies’’ could effectively resolve this issue. If the same personnel aid the same designated residency every time they are needed when a natural disaster hits, the relearning of information and the retraining of procedures are limited.

The interaction of the state transportation agency field units and the emergency-operations center should be examined to develop a systematic way of delegating and prioritizing recovery activities. Currently, the emergency-operations center assigns tasks to their field forces according to the precedence of human life and safety over property and property over the environment (Susan Toth, personal communication, October, 2000). This approach lacks efficiency in that there is no further task classification to follow for determining the order of completion within these three general priorities of (1) human life, (2) property, and (3) environment. For instance, if multiple calls come into the transportation emergency-operations center requiring field response and they all have potential to harm the environment in relatively the same capacity, how should the emergency operations center decide which task to send field units to first? A tool could be created within the transportation agency's information system that prioritizes tasks and equipment requests based on input from field personnel regarding their urgency.

Measuring and Comparing Dependency Scenarios

Methodology for Measuring Dependency Scenario

Along with a categorical analysis to indicate the agency units needing improvement, schedule dependency scenarios can be

Table 5. Summary of Index Definitions for Measuring Magnitude of Dependency Scenario According to Three-Level Scale

Indices	Low	Moderate	High
Severity	Table 4	Table 4	Table 4
Involved agencies	No other agencies	Few agencies	Multiple agencies
Likelihood	Unlikely to occur	Has not occurred in the past, but likely to occur	Has occurred in the past, likely to occur again
Items waiting on (personnel, materials, equipment, authorization)	None	One item	Combination of many
Controllability	Controllable at low cost	Controllable at high cost	Uncontrollable
Cascading effects	None	One	Multiple
Maturity	Mature	Immature	Highly immature
Number of similar scenarios	None	Few	Many

J. Infrastruct. Syst., 2002, 8(3): 103-111

Table 6. Values of Each Index for Example Dependency Scenario

Severity	Involved agencies	Likelihood	Items waiting on	Controllability	Cascading effects	Maturity	Number of same scenarios
Hours in short term	Few other agencies	Has occurred in the past, likely to occur again	Information only	Controllable at low cost	Few	Mature	Many
Moderate	Moderate	High	Moderate	Low	Moderate	Low	High

measured and compared. The transportation agency can determine those dependencies that are most critical and then take the appropriate steps to resolve the critical scenarios.

Dependency scenarios can be measured using eight indices that express the ''size'' of the dependency according to a three-level scale: *low*, *moderate*, and *high*. The first index represents the severity of the dependency in terms of the length of time involved relative to a time horizon, which is either classified as the short-term following the disaster (hours, days), the medium-term (days, weeks), or the long-term (months, years). Table 4 demonstrates how severity is measured according to the three-level scale.

The second index takes into account the agencies affected by the dependency. A value of *low* is given if the scenario is an intraagency dependency occurring within the state transportation agency in which no other agencies are involved. If the dependency involves a few other agencies, a value of *moderate* is given, and if it involves multiple other agencies a value of *high* is given. The third index represents the likelihood or potential for the dependency to occur in the future. If the dependency is unlikely to occur in the future, it is given a value of *low*. A value of *moderate* indicates that the dependency scenario has not occurred in the past, but is likely to occur in the future nonetheless. If the dependency has occurred in the past, and is likely to occur again, it is assigned a value of *high*.

The fourth index takes into account the items another agency is waiting to receive from the transportation agency or vice versa, which range from personnel, to materials and equipment, to authorization, etc. This index is measured on the three-level scale according to the number and combination of items involved. The fifth index measures controllability, which is the ability to control the cause(s) or components of the dependency. A value of *low* indicates that a resolution for the dependency can be developed for the future at a low cost. If alternatives are being considered for the future, but a resolution for the dependency would have a high cost, it receives a value of *moderate*. A value of *high* is given to a dependency if nothing can be done to avoid this dependency in the future.

The sixth index concerns the cascading effects brought on by the dependency. Cascading effects signify the scope of the succession of the subsequent dependencies, delays, and/or problems that arise from the dependency scenario, or the extent to which the dependency serves as input to more dependencies and delays. The effects are measured according to the magnitude of this scope. The seventh index measures the maturity of the dependency. Maturity represents the level of preparation and development associated with the procedures or activities involved. An example is the level of training performed and instruction received by the workforce involved or the extent to which the procedures involved have been practiced. Finally, the eighth index measures the prevalence of similar dependency scenarios, which account for whether the scenario is an isolated instance, or if it occurs in numerous situations. All eight indices and the definitions of how they are measured are summarized in Table 5.

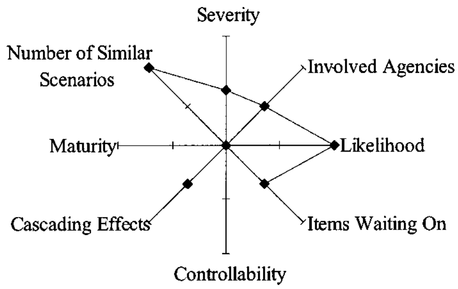

Fig. 4. Representation of sample dependency scenario (SD.07, Table 1) according to values measured for each index

Demonstration of Indices

A dependency scenario is measured in Table 6 using the eight indices. This type of dependency is assumed to have a high likelihood of happening again in the future because the transportation agency's existing system is not capable of displaying real-time road conditions on a very recurrent basis. The system is currently updated with new information every 4 hours (Susan Toth, personal communication, October, 2000). In addition, on-site personnel do not have the ability to automatically input information themselves from the field. A system with these features is assumed to be available at a relatively low cost. The dependency can be better understood using graphical representation as shown in Fig. 4.

The graphical representation also provides a medium for comparing the magnitudes of multiple scenarios. Fig. 5 gives a comparison of scenarios across the eight indices. For instance, the top left graph represents a dependency (SD07) that has moderate severity, a few other agencies involved, has occurred in the past, is likely to occur again, involves one item being waited on, is controllable at a low cost, has few cascading effects, is mature, and presents itself in many other similar scenarios. The bottom right graph, in contrast, represents a scenario (SD48) that has high severity, no other agencies involved, has occurred in the past, is likely to occur again, involves one item being waited on, is controllable at a high cost, has multiple cascading effects, is mature, and is not similar to any other scenarios, it is an isolated instance of a dependency. With the apparent differences between the two scenarios, they may be regarded and resolved differently by agency planners.

Conclusions

Coordination within the transportation agency and among the agencies involved in the pre and postdisaster processes can be improved in order to minimize the time it takes a region to fully recover from a natural disaster. This paper has contributed a methodology in which dependency scenarios are subjected to a categorical and comparative analysis, which can aid a transportation agency's recovery planning and subsequently reduce the overall time to recovery following a hurricane or other regional disaster. According to the analysis of a sample of dependency

J. Infrastruct. Syst., 2002, 8(3): 103-111

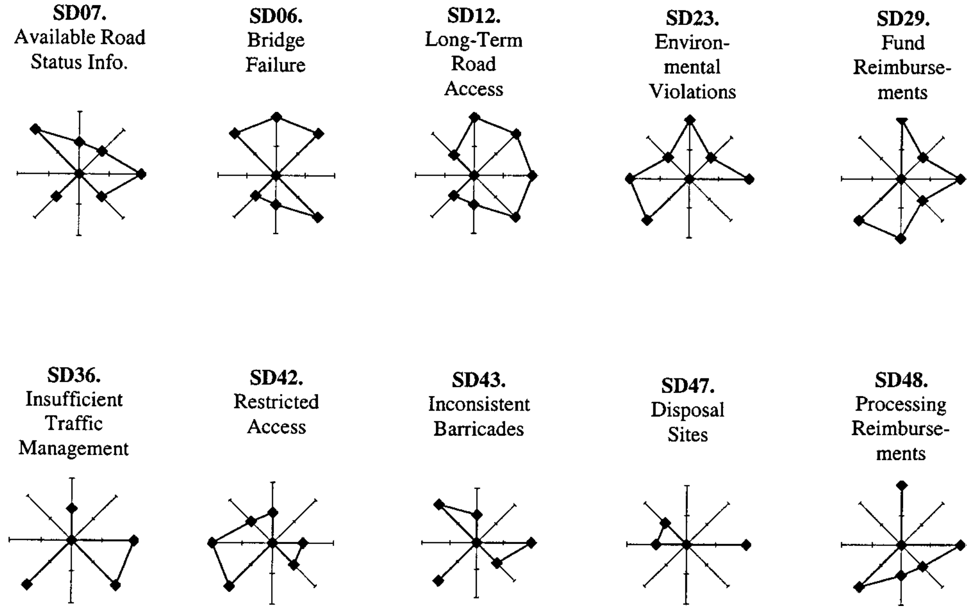

Fig. 5. Framework for comparison to highlight critical schedule dependency scenarios arising during hurricane recovery using eight indices developed

scenarios collected from various state and local agencies in Virginia, California, Florida, North Carolina, and South Carolina, the *Information Management* unit and *Operations* unit are the sources of numerous past and potential schedule dependencies. In particular, the analysis of the pairs of organizational units shows that the interaction of the *Information* unit with the *Operations* unit and the *Operations* unit and *Structure and Bridge* units introduce a significant number of dependencies. It is described that improved recovery coordination can be achieved by increasing the interagency accessibility of shared information.

The findings of the paper's case studies should not be a sole basis for planning. First, it is important to realize that, except for the methodology developed, the findings are based on the interviews whose results are subject to the biases of individuals. The anecdotes of individuals may have been used expediently as representative of an entire agency. Corrective strategies may be needed to ensure representative results from such an interview process. Next, the number of usable responses received to the questionnaire is small relative to the number of agencies initially contacted. Because the response rate is low, the group of agencies that actually contributed to the dependency scenario collection may not be representative of all agencies involved in recovery. As shown in Fig. 6, the number of each type of agency (communication, environmental, fire, health, military, police, transportation, utility) is not equally distributed; environment and health-related agencies together overbalance other sources of scenarios. Though a team of 1,000 interviewers would not uncover all potential and past dependencies, the collection of scenarios would certainly be more representative than the small sample described herein. Future investigation of schedule dependencies in disaster recovery should include an expanded scenario collection for results that are representative of the agencies involved. Individual scenarios that are given high priority in the developed methodology can be analyzed further using PERT, an activity network modeling tool, to identify recovery activities on the critical paths. An analysis of the tradeoffs between prehurricane investments of resources and time to recovery should be performed on the alternatives identified from the PERT models. The developed methodology can be applied across a variety of geographical scales, types of disasters, and public agencies.

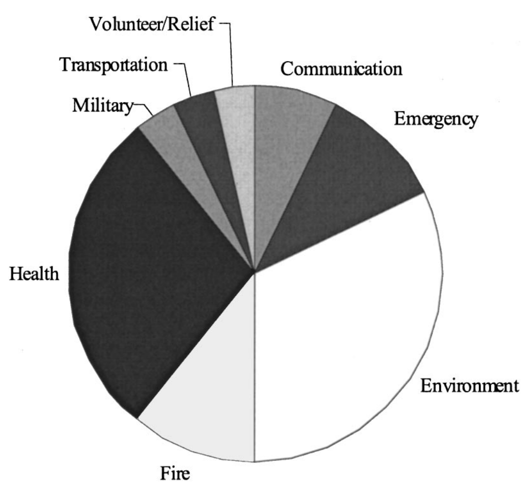

Fig. 6. Number of interagency schedule dependency scenarios in sample for each type of agency involved

Acknowledgments

The writers would like to thank the following individuals and agencies for their contributions to this paper: Mr. Wayne Ferguson of the Virginia Transportation Research Council; C. Everette Vaughan, Jr., Director of Emergency Operations at the Virginia Office of Emergency Medical Services; Louis Cox, Hall Ambulance Service, Inc., California; Kelly Hutchinson of the NCDOT; Profs. Yacov Y. Haimes and Garrick E. Louis, University of Virginia. Particular thanks goes to the following members of the Virginia Department of Transportation Steering Committee: Travis Bridewell, Mac Clarke, Perry Cogburn, Jon DuFresne, Stephany Hanshaw, Steve Mondul, Murali Rao, Bob Rasmussen, J. R. Robinson, and Gerald Venable.

J. Infrastruct. Syst., 2002, 8(3): 103-111

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J. Infrastruct. Syst., 2002, 8(3): 103-111