DYNAMIC REAL-TIME ROUTING FOR EVACUATION RESPONSE PLANNING AND EXECUTION

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**Abstract**

This study addresses the problem of dynamic routing operations in the emergency response context, primarily in terms of the routing of response vehicles and evacuees. The study focuses on identifying the paths used for routing response vehicles and the evacuees in disaster situations. In this context, two application modules are developed: module for K-shortest paths routing and module for multiple-stop routing. The K-shortest paths module allows more flexible options for routing response vehicles under the dynamic network conditions due to a disaster. It provides multiple routes for evacuation and response operations. The multiple-stop routing module enables the delivery of relief resources to several locations using a single response vehicle. It has the ability to impose time window constraints for relief operations and the reordering of the routing to the delivery locations, capabilities which are critical to disaster operations.

For ease of operability, these modules are developed on a Geographic Information System (GIS) platform used by the Indiana Department of Transportation (INDOT) and Indiana Department of Homeland Security (IDHS). Based on dynamic field conditions, color-coded flags on the GIS map are used to characterize links in terms of their availability and functionality in the context of the response operations. These link characteristics are dynamically updated as new information on the network conditions becomes available over time. The proposed modules can be integrated into the current web-based traffic information system called TrafficWise supported by INDOT and disaster management system Web Emergency Operation Center (WebEOC) supported by IDHS for seamless practical implementation.
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EXECUTIVE SUMMARY

DYNAMIC REAL-TIME ROUTING FOR EVACUATION RESPONSE PLANNING AND EXECUTION

Introduction

Strategic planning for emergency response is critical for effective response to natural or deliberate disasters. Response vehicle routing and evacuation of the affected people are part of emergency response operations under disasters. The response vehicle routing seeks to rescue the distressed population and deliver relief support to the affected locations in minimum time, while the evacuation component aims to quickly relocate the affected people to safe locations. The difference between these activities is that they are typically conducted in opposite spatial directions, that is, to and from the affected area, respectively. This characteristic of emergency response operations presents challenges in terms of routing, in addition to time constraints. Moreover, the road network state under a disaster can be time-dependent, since the link (or node) capacity/availability is known only after the disaster occurs (or spreads), and as information is received or updated over time.

This study addresses the problem of dynamic routing operations in the emergency response context, primarily in terms of the routing of response vehicles and evacuees. The study focuses on identifying the paths used for routing response vehicles and the evacuees in disaster situations. In this context, two application modules are developed: a module for K-shortest paths routing and a module for multiple-stop routing. The K-shortest paths module allows more flexible options for routing response vehicles under the dynamic network conditions due to a disaster. It provides multiple routes for evacuation and response operations. The multiple-stop routing module enables the delivery of relief resources to several locations using a single response vehicle. It has the ability to impose time window constraints for relief operations and reorder the routing to the delivery locations—capabilities that are critical to disaster operations.

Findings

- Some links may not be functional after a disaster. To provide flexible routing options for the emergency responders and evacuees, there is a need to generate multiple routes (such as the shortest, 2nd shortest, 3rd shortest, etc.) so that if a route is not available or is congested, the next best route can be provided. This can be done by using a K-shortest path algorithm to generate multiple routes.
- The paths obtained from the K-shortest path algorithm should not overlap each other significantly so as to avoid redundancy in routing. Significant overlap may result in limited usefulness during response operations, should link failures or congestion occur.
- In response operations, there is a need to deliver relief resources (e.g., food, medicine, etc.) to several locations by each response vehicle in a trip. This introduces the problem of multiple-stop routing. Further, the deliveries to some stops may be subject to time window constraints, whereby the stops should be ordered in a certain manner such that the resources can be delivered within the pre-specified time limits.
- The K-shortest paths module provides the functionality to generate K-shortest paths based on the dynamic network conditions such that the generated paths are mostly distinct. That is, the generated paths do not share a significant proportion of common links.
- The multiple-stop routing module can be used in situations where relief resources need to be delivered to several locations (stops) using one or a limited number of response vehicles. This module supports the shortest path routing across multiple stops. This is critical in disasters when there is a priority associated with the stops to be visited, or there are time constraints for the delivery of relief resources at some stops.
- In the multiple-stop routing module, any violations of time windows are indicated so that the operators can further re-arrange the fleet. If no priority of deliveries to the stops is imposed, the module can support re-ordering to achieve the shortest travel time.

Implementation

Two modules, the K-shortest paths and multiple-stop routing modules, are developed on a Geographic Information System (GIS) platform used by the Indiana Department of Transportation (INDOT) and Indiana Department of Homeland Security (IDHS). Based on dynamic field conditions, color-coded flags on the GIS map are used to characterize links in terms of their availability and functionality in the context of the response operations. The link characteristics are dynamically updated as new information on the network conditions becomes available over time. The two modules will be integrated into the current web-based traffic information system called TrafficWise supported by INDOT and disaster management system Web Emergency Operation Center (WebEOC) supported by IDHS for seamless practical implementation. A step by step manual has been provided for the implementation of the modules.
CHAPTER 1. INTRODUCTION
1.1 Background and motivation

Strategic planning for emergency response is critical to address the immediate and potential life-threatening dangers posed by natural or man-made disasters. Response vehicle routing and evacuation of the affected people are part of emergency response operations under disasters. The response vehicle routing seeks to rescue the distressed population and deliver relief support to the affected locations in minimum time; while the evacuation component aims to quickly relocate the affected people to safe locations. The difference between these activities is that they are mostly conducted in opposite spatial directions of each other, that is, to and from the affected area, respectively. This characteristic of emergency response operations makes them challenging in terms of routing, in addition to time constraints.

Disasters can cause failure or capacity degradation of the elements of a road network, for example, bridge breakdown due to earthquake or inundation due to flood. The level of destruction may vary for different disaster types based on the disaster characteristics and network topology of the impacted area. Some of the disasters and their possible impacts on the road network are summarized in Table 1.1.

The road network state under a disaster can be time-dependent, since the link (or node) capacity/availability is known only after the disaster occurs (or spreads), and as information is received or updated over time. Based on the updated link (or node) information, the strategic routing for both response vehicles and evacuees can be planned. In the evacuation context, both link availability and capacity are critical in terms of assigning the surging demand to the limited capacity of the road network. By contrast, for routing of the response vehicles, link availability is more important than link capacity. This is because the key need for the routing of response vehicles is the connectivity from a response/rescue center to the disaster sites.

The literature addresses some of these issues by developing a framework for dynamic routing of traffic. In a previous JTRP study, Peeta and Kalafatas (2007) propose an operational framework for the dynamic rerouting of response vehicles in post-earthquake roadway system, but not the routing of evacuees. The present study extends the Peeta-Kalafatas framework to enable response operations which include the routing of both response vehicles and evacuees.

In the extended framework, shown in Figure 1.1, the routing starts with the initial network conditions stored in a static database. The routes for the response vehicles and the evacuees are computed in the routing component after verifying the link availability along the routes for the various origin-destination (O–D) pairs. Since some links may not be functional after a disaster, to provide options for the emergency responders, there is a need to generate multiple routes (such as the shortest, 2nd shortest, 3rd shortest, etc.) so that if a route is not available the next best route can be provided. This is done by using a K-shortest path algorithm (Ahuja et al. 1993) to generate multiple routes. If a link in a route is not available, then its status is updated in the dynamic database and the routing component re-calculates the K-shortest routes based on the updated network conditions. This process is repeated until the availability status of all links is verified in the dynamic route identified to generate the route for the response vehicles.

The above framework is sufficient for response operations in contrast to specifying only a single shortest route which can lead to its capacity being exceeded. This can be observed when a large population is trying to evacuate from the affected area at the same time using a well-known route. Therefore, in addition to the shortest route, other feasible shortest routes in terms of travel time are identified using the K-shortest path algorithm. Hence, in this study we employ the above framework for response operations and the concept of K-shortest routes for developing the specific modules for the routing of response vehicles and evacuees.

During the response operations, there may be the need to deliver relief resources (e.g. food, medicine, etc.) to several locations by each response vehicle in its corresponding trip. This motivates the problem of multiple-stop routing (Golden and Assad 1988).

<table>
<thead>
<tr>
<th>Disaster</th>
<th>Link failure (Link capacity degradation)</th>
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<tr>
<td>Flood</td>
<td>• Bridge breakdown (complete link failure)</td>
</tr>
<tr>
<td></td>
<td>• Water inundation (link capacity reduction or complete link failure)</td>
</tr>
<tr>
<td></td>
<td>• Mudslide (link capacity reduction or complete link failure)</td>
</tr>
<tr>
<td></td>
<td>• Washout (complete link failure)</td>
</tr>
<tr>
<td>Terrorist attack</td>
<td>• Route / link / lane closure (link capacity reduction or complete link failure)</td>
</tr>
<tr>
<td>Wild fire</td>
<td>• Route / link / lane closure (link capacity reduction or complete failure)</td>
</tr>
<tr>
<td></td>
<td>• Smoke (link capacity reduction or complete link failure)</td>
</tr>
<tr>
<td>Earthquake</td>
<td>• Bridge breakdown (complete link failure)</td>
</tr>
<tr>
<td></td>
<td>• Road destruction (link capacity reduction or complete link failure)</td>
</tr>
<tr>
<td></td>
<td>• Debris / falling objects (link capacity reduction or complete link failure)</td>
</tr>
<tr>
<td>Hazmat accident</td>
<td>• Route / link / lane closure (link capacity reduction or complete link failure)</td>
</tr>
</tbody>
</table>

TABLE 1.1. Various types of disasters and their impact on the road network
Moreover, the deliveries to some stops may be subject to time window constraints, whereby the stops should be ordered in a certain manner such that the resources can be delivered within the pre-specified time limits. Based on the implementation platform used by the INDOT (ArcGIS), any inevitable violations of the constraints in the output route should be indicated as well, so that the operators can further re-arrange the fleet of response vehicles. This issue has been addressed in this study by applying the concept of multiple-stop routing with time window constraints.

1.2 Problem statement

This study addresses the problem of dynamic routing operations in context of disaster management. The major focus is to identify K-shortest paths for routing response vehicles and evacuees. The challenges lie in identifying the K-shortest paths for response operations in the dynamic network and the need to optimally deliver the relief resources to several locations by each response vehicle within the given time constraints.

1.3 Study objectives

As discussed in the previous sections, the focus of this study is on the operational needs of response vehicles under disasters, including multiple-stop routing and identification of K-shortest paths. The module for multiple-stop routing is used for the routing of response vehicles to multiple locations in a single trip. The module to identify K-shortest paths can be employed to determine strategic routes for response operations. It is also used for the route guidance of evacuees. Hence, the objectives of the study are to:

1. Develop a module for K-shortest paths generation: The K-shortest paths between an O-D pair are generated based on the current network conditions, and typically identified in the order of ascending travel times from the origin to destination.

2. Develop a module for multiple-stop routing of response vehicles: The routes for delivery of relief materials at different locations using various vehicles within the time constraints is generated based on the current network conditions. In addition, any inevitable violations of the constraints in the output routes are indicated as well, so that the operators can further re-arrange the fleet of response vehicles.

Both modules are integrated with the current Geographic Information System (GIS) platform used by the INDOT and the Indiana Department of Homeland Security (IDHS), where the dynamic field conditions are represented using color-coded flags on the GIS map. The flags are used to characterize links in terms of their availability and functionality in the context of the response operations. These link characteristics are dynamically updated as new information on the network conditions becomes available over time.
Also, the output routes need to be graphically displayed onto GIS maps, which will enable the operators to easily recognize the routes/links and other possible risks so as to facilitate deployment.

1.4 Work plan

Currently, INDOT hosts TrafficWise, which is a web-based traffic information system supporting the on-line inquiries related to traffic conditions and road availability on a Google Map base. Additionally, the WebEOC software used by the IDHS as its response implementation platform is an ArcGIS Server based information system for disaster management, and contains a geo-database with disaster maps (primarily for flooding). INDOT plans to use an infrastructure monitoring system to input the network dynamics into its ArcGIS platform. In this monitoring system, the link status is identified and reported by trained personnel from the field to the management center and is updated in real-time on the TrafficWise system. The links conditions are marked onto the GIS map with three types of flags, each representing a different link status as:

- Green flag signifies that the link is functional. (No impact of the disaster on the link, or the impact on the link can be neglected.)
- Yellow flag signifies the link is partially functional and only available for response vehicles with some restrictions. (The link sustains a certain level of damage but is still usable for response vehicles with restrictions like maximum height of response vehicle, maximum weight of response vehicle etc. and is not allowed for use by the evacuees.)
- Red flag signifies that the link is not functional. (The link is severely damaged.)

This update mechanism is utilized as the base for obtaining network dynamics in this study. Based on the ArcGIS platform, this study focuses on developing modules for dynamic routing, which can assist INDOT in developing strategies for emergency response.

The next chapter reviews the literature in the context of the problem, including theoretical and practical issues related to routing techniques, and relevant GIS applications. In the third and fourth chapters, the two application modules are described. The first module is for K-shortest paths routing and the second module is for multiple-stop routing with time window constraints. The execution of the modules is explained using detailed illustrations. In the last chapter, concluding comments are presented that summarize this study and provide directions for future research.

CHAPTER 2. LITERATURE REVIEW

This chapter provides a brief review of the methodological and practical aspects relevant to the dynamic routing operations for disaster management. Section 2.1 discusses the literature and characteristics of the K-shortest path problem. Section 2.2 introduces the GIS techniques, specifically the application of GIS software for disaster response. Section 2.3 summarizes the issues and identifies the characteristics of the proposed K-shortest path approaches.

2.1 K-shortest Path Problem

For disaster response operations, the primary concerns are identifying available links for routing, and the routing of response vehicles and evacuees. In response operations, the focus is on routing based on the minimum travel time to deliver relief resources to the affected population under dynamic network conditions. In the context of identifying evacuation routes for a response operation, the notion of K-shortest paths algorithm is introduced by Campos et al. (1999) so that large numbers of vehicles can be assigned to “K” preferable paths to minimize the network clearance time, instead of relying on a single “optimal” path. The K-shortest path problem can be viewed as an extension of the shortest path problem. One common approach to solve the K-shortest path problem is to extend the label-setting and label-correcting approaches generally used to determine the shortest path, such as Dijkstra’s Algorithm. Instead of using a single label at each node, an array of K-labels are used, so that paths can be recorded and sorted in an ascending order in terms of the objective (Ziliaskopoulos 1994). Such an approach provides the K-shortest paths for a feasible path set. However, if these paths overlap each other significantly (high dependency across the paths), they may be considered as almost identical by decision-makers for some applications, limiting their usefulness (Park and Rilett 1997). There are a few heuristic approaches for solving K-shortest path problem, which can be categorized into three groups: elimination techniques, overlapping penalty approaches, and branching methods (Ramming 2002). In the elimination technique, links of the derived shortest paths in the network are removed one at a time, and the approach is repeated to identify the next shortest path. In overlapping penalty approaches, the impedance of overlapped links is increased along the existing shortest path before searching for the next shortest path. The branching method selects a set of consecutive links from the previously-identified shortest path and joins them to the origin and the destination using other links. These approaches provide an approximate solution for the K-shortest path problem for a given network (Ramming 2002). A comparative study of various K-shortest path algorithms can be found in Ahuja et al. (1993) and Brander and Sinclair (1995). In this study, we use the overlapping penalty approach to solve the K-shortest path problem as it avoids large overlaps between links in the selected routes.

In disaster situations, apart from multiple shortest paths, there may be a need to deliver the relief resources to several locations using a single vehicle. It requires the routes and stops to be chosen such that the vehicle delivers the resources at multiple stops using minimum
time under time window constraints. This problem is called multiple-stop routing under time window constraints. Hence, if there is a particular order in which the vehicle has to visit each location in the route determined, the problem can be viewed as a sequence of shortest path problems between successive locations. However, if there is no fixed order for visiting stops, then the route between the origin and the destination can be determined using the classical traveling salesman problem, which is NP-hard. More discussion on these problems and their variants can be found in Golden and Assad (1988).

2.2 Application of GIS techniques

GIS is a critical application platform in geography and regional science. GIS can relate different data sources onto a unified map platform according to a certain coordinate system. Each data source is constructed into a layer, which contains the corresponding data with their spatial characteristics and allows graphical displays. Based on the adopted coordinate system, data can be spatially referenced across different layers, enabling an integrated analysis. Due to its capability for managing spatial data, GIS has been widely applied to the domains of disaster response and transportation system management. Further, the incorporation of global positioning system (GPS) broadens the application of GIS in both planning and operational contexts. Extensive reviews of GIS application to disaster responses and transportation systems are provided by Amdahl (2001), Briggs (2002), and Hensher (2004).

ArcGIS is the GIS software used by IDHS for its disaster management system titled Web Emergency Operation Center (WebEOC). The latest version, ArcGIS 9.3, provides a functional extension, named Network Analyst. The ArcGIS Network Analyst supports network-based tasks, and more specifically tasks executed in transportation networks. Its major functionality is to calculate the shortest path based on the given network traffic conditions (e.g. link travel time) and restrictions (e.g. height limits, speed limits, turning radius etc.). Based on this functionality, the ArcGIS Network Analyst enables a broad range of applications, including drive-time analysis, point-to-point routing, fleet routing, service area definition, and closest facility analysis (ESRI 2007). According to plan proposed by the INDOT, the real-time traffic and travel time feed of various links from TrafficWise system will be integrated to the ArcGIS-based WebEOC system. This will entail the development of modules that can support K-shortest paths routing and multiple-stop routing in disasters. In this study, we seek to develop these modules.

2.3 Discussion

The main operational tasks in this study include K-shortest paths routing and multiple-stop routing. GIS techniques provide a platform for managing the information which has geographic or spatial implications. The disaster management application used by IDHS, and to be integrated with TrafficWise program of INDOT, is based on ArcGIS and needs some additional critical functionalities like K-shortest path and multiple-stop routing. We use the overlapping penalty approach for the K-shortest path problem. The Network Analyst tool box of ArcGIS is used to provide the functionalities for multiple-stop routing. The next chapter discusses the module for K-shortest paths routing. Chapter 4 discusses the module for multiple-stop routing on the ArcGIS platform.

CHAPTER 3. MODULE FOR K-SHORTEST PATHS ROUTING

To enable operability with the disaster management platform to be used by INDOT and reduce potential interface and integration issues, this study develops the routing modules directly on the ArcGIS platform. ArcGIS provides a module development environment, where developers can utilize an in-built component, called “Arc Toolbox”, which facilitates the development based on the existing interface of data and graphical displays. Section 3.1 introduces the methodological concepts adopted to develop the K-shortest paths routing module. In section 3.2, a basic procedure to establish a network dataset (ND) is described. Section 3.3 describes a step-by-step procedure of routing operations for a disaster scenario using the Indianapolis city network.

3.1 Methodology for K-shortest paths routing

As introduced in section 2.1, the K-shortest paths can be obtained using K-label-setting or K-label-correcting approaches. However, these methods cannot preclude the possibility of obtaining overlapped paths. That is, the obtained paths may share common links for a large proportion of their lengths. But for routing under disasters, the operators require a set of paths that do not overlap significantly, as the operators of response vehicles need to evaluate the potential risks on different paths and choose the response paths accordingly. Additionally, for evacuation operations, the demand from a certain zone can be distributed to different routes, instead of being directed to links that overlap on several evacuation routes. To obtain a set of operational paths that are distinct to some extent, an overlapping penalty approach is employed in this study. Once the shortest path is generated, this approach scales up the costs on the links along this path. Then, the next shortest path is calculated based on the new network characteristics. In this approach, the links of the previously generated shortest paths are still available for the determination of the next shortest path, but the increased costs will reduce the possibility of most of these links appearing in the next path. The overlapping penalty approach can be viewed as a generalization of
an elimination approach, where the links of the previously computed shortest paths are removed from the network (equivalent to assigning very high costs to these links). In addition, the value used for scaling up implies a trade-off between the need to reduce overlap and ensure accuracy. A higher (link cost) value can lead to lower overlap across the generated routes but also increase the approximation to the actual K-shortest paths. In this study, we scale up the costs of links by multiplying the original costs (link travel time) by a factor 1.5. This value can be increased or decreased based on the network characteristics. Since Indianapolis is a dense network, an increase of 50% can reduce the likelihood of such links from being considered in the next shortest path.

3.2 Establishing network dataset

The Indianapolis city street map (Streetmap NA) provided by INDOT is used as the study network for illustrating the functionality of the modules. The Streetmap NA provides only link-specific attributes such as street name, road class, length, etc., but not how links connect with each other (that is, the network structure). Therefore, to enable network-based analysis on the ArcGIS platform, we must first establish a network dataset from the street map source of the study area. This can be done using ArcCatalog, a sub-program of ArcGIS, which is the core system for GIS data management. The network dataset for this study can be built according to the following procedure:

1. Open ArcCatalog and go to the folder with the source street map, which is in a shapefile (.shp). In this study, we name the file as Majorroad.shp.
2. Click “Tools” in the toolbar and select “Extensions” from the menu. From the Extensions dialog box, check “Network Analyst” to enable it.
3. Right click the Majorroad shapefile under the “Contents” tab and select “New Network Dataset…” to start the wizard for network dataset establishment.
4. Specify a name for the network dataset. It is set to Majorroad_ND by default. Click “Next” to continue.
5. In the following dialog boxes (Figure 3.5), we use the default settings for connectivity, turns, driving directions, etc. in the ArcGIS software in this study (for a specific traffic network, they can be modified based the actual network conditions and operational needs), by clicking “Next” in the popup windows for the network dataset. We add Travel Time (TT) as an attribute for the network dataset. To do this, in the dialog box for specifying the network attributes, click the button “Add…”, and key in TT for name and select Minutes from the “Data Type” dropdown for the units.
6. In the summary dialog box, click “Finish” to create the new network dataset shapefile.
7. Click “Yes” from the dialog box to build the network dataset.

The network dataset of Indianapolis roadway system is now ready. The network dataset shapefile, Majorroad_ND, is added to the “Contents” tab of ArcCatalog along with a system junctions shapefile (representing road intersections) called Majorroad_ND Junctions.

Figure 3.1. Opening the network files
3.3 Operation of K-shortest paths routing

ArcMap is another sub-program of ArcGIS, which is the core system that combines the layers of different data sources onto a map with a unified coordinate system that provides an integrated graphic display. GIS-based analyses can be conducted on this map platform with cross-layer spatial referencing. The operations of Network Analyst need to be performed on ArcMap, and the proposed module for K-shortest paths routing can be added based on the functionality of Network Analyst. An example of K-shortest paths routing and re-routing is provided hereafter:

A. Preparing the display and settings for K-shortest paths routing

First, set up the display interface on the ArcMap window using the following steps:

1. Open ArcMap and the project (.mxd file) to work on, along with the corresponding data layers.
2. Click “Tools” in the window menu and select “Extensions”. From the Extensions dialog box, check “Network Analyst” to enable it.

Figure 3.2 Enabling Network Analyst in ArcCatalog

Figure 3.3. Building a network dataset from street map files

Figure 3.4. Naming the file of the network dataset
3. Click “View” in the window menu, point to “Toolbars”, and check “Network Analyst” to add the toolbar of Network Analyst to the current display.
4. Open the Network Analyst window by clicking the “Network Analyst Window” button on the Network Analyst toolbar.
5. Click the “Show/Hide ArcToolbox window” button to open the ArcToolbox window, and expand the Network Model toolbox, which contains three developed models: “Find the First Path”, “Find the Next Path”, and “Dataset Recover”.

B. The operation of K-shortest paths routing

1. On the Network Analyst toolbar, click the Network Analyst dropdown, and select “New Route” from the menu to create a route analysis layer (which will contain empty sub-layers of Stops, Routes and Barriers).
2. Click the “Route Properties” button at the upper-right corner of the Network Analyst window. In the prompted dialog box, first click on the tab of “Analysis Settings”, and then select the impedance from the dropdown (in this example, we use TT (Travel Time) as the impedance). Next, check “Use Time Attribute” and “Open Directions window automatically” in the “Directions” box. Then, in the tab named “Accumulation”, check both TT and Miles; this results in the output related to the path determined in terms of its total travel time and distance.
3. Click Stops(0) in the Network Analyst window, and then in the Network Analyst toolbar click the “Create Network Location Tool” button. Next, click the location of the dispatch center on the map as Stop 1, and then click the location with the population requiring assistance (affected area) on the map as Stop 2. In the Stops sub-layer in the Network Analyst window, the added stops are listed as Graph Pick 1 and Graph Pick 2 as shown in Figure 3.16.

If any locations are re-defined, the stops can be relocated using the “Select/Move Network Locations Tool” button on the Network Analyst toolbar. This also requires dragging the stops to the new locations using the mouse. After locating the stop, remove the selection on the stop by right-clicking the stop and selecting “Clear Selected Features” (Figure 3.17); otherwise, the selected stop is not recognized by the Network Analyst. After removing the selection, the turquoise highlight on the stop will disappear.
4. Open the “Find the First Path” model in the ArcToolbox (as in Figure 3.18) window by right clicking the model and then selecting “Edit”. The model is built using the tools in the Arc Toolbox to construct the desired workflow of data calculation. Run the model by clicking “Model” in the window menu and selecting “Run Entire
A script of the execution procedure of the model will appear as in Figure 3.19. The (first) shortest path will be displayed on the map, and simultaneously in the Network Analyst window. The information of the shortest path is added to the Routes sub-layer, which is initially empty. Also, a window showing the turn-by-turn directions will be automatically generated (Figure 3.21). This directions window provides turn-by-turn path details and the accumulation of travel time and distance along the path. The information of the directions window is stored in temporary memory space and will be deleted or overwritten by the next action. If the users need this information later, they can save it to other physical storage by clicking the “Save As…” button and providing a path to the location for saving the information.

5. To find the next best path, we first need to scale up the costs of links along the obtained shortest path, and then repeat the shortest path analysis based on the updated network. This can be done by running the “Find the Next Path” model in the Arc Toolbox window similar to “Find the First Path” model in Step 4. The second shortest path is generated and displayed on the map. However, now the information of the first
shortest path in the Routes sub-layer is overwritten with the information of the second shortest path. To allow the retrieval of the information of the first shortest path, the proposed module automatically saves the information on the generated paths into another pre-set layer, named KSP. It can be found in the window of active data maps. Right-click KSP layer and select “Open Attribute Table”. It will prompt the table which records the information on the paths in an ascending order in terms of path travel time. Two path attributes are present, path travel time in field “Total_TT” and path length in field “Total_Len”. Selecting the path from the table will also highlight the path on the map so as to help identify the order of the generated paths.

6. Repeat Step 4 to obtain the next shortest path until the desired number of shortest paths are generated (as in Figure 3.24).

7. After finishing the search for the K-shortest paths, run the “Dataset Recover” model in the ArcToolbox window to recover the network to the initial cost settings.

C. The operation of re-routing

The operation of re-routing is necessary, when link failure occurs on an identified shortest path. That is, we need to find a new shortest path which avoids the failed links. In the aftermath of a disaster, the field conditions will be reported by INDOT personnel to the response center. Based on the field conditions, the links will be characterized in terms of their availability and functionality in the context of the response operations. The color-coded flags will be used on the GIS map to...
characterize these links. In the Network Analyst tool, this link failure can be indicated on the map as a barrier. Here, we first differentiate between the types of link failure and their effects on the routing operation. For the evacuees, both red flag and yellow flag implies the unavailability of the tagged link and can be viewed as barriers in the network system. However, for the response vehicles operation, the yellow-flag link is considered to be still usable but with some restrictions like height, weight etc. of the response vehicles. In this example, we consider the re-routing operation of response vehicles and illustrate how the proposed module addresses the issues of interest in the following procedure:
Figure 3.14. Creating a new route analysis layer

Figure 3.15. Setting Network Analyst

Figure 3.16. Adding the O-D to the route analysis layer
1. To add a red flag to the map, click Barriers (0) in the Network Analyst window, and click the Create Network Location Tool button on the Network Analyst toolbar. Then, click the location of the reported link failure on the map with the representation of the adopted red symbol. We recommend zooming-in to the location of link failure while adding the barrier; otherwise, the barrier added by clicking on the map may not precisely attach to the link where the failure is identified.

2. While re-routing, it is advisable to first to remove the selection on the stop by right-clicking the stop and selecting “Clear Selected Features”. Also, the “Dataset Recover” Model needs to be run to clear the previously obtained shortest paths (before updated network conditions). Next, conduct the K-shortest paths routing as introduced in B (run “Find the First Path” and “Find the Next Path” models). The new shortest paths will be generated and displayed on the map, which can be used for re-routing vehicles. In the re-routing context, it must be noted that the newly generated path is different from the second shortest path derived from the K-shortest paths module. In the K-shortest paths routing approach used, the generated paths are designed to be significantly different from each other. By contrast, the new path here is re-generated to circumvent the identified barrier only, but a significant proportion of the original shortest path is still used. As shown in the example in Figure 3.26, there is a good overlap between the original and the newly generated shortest paths (obtained by avoiding the barrier).

3. To add a yellow flag to the map (which means link is available only for response vehicles with some restrictions), we create another route analysis layer for the yellow flag representation. To create another routing analysis layer, on the Network Analyst toolbar, click the Network Analyst dropdown, and select “New Route” from the dropdown to create a new route analysis layer, with default name “Route 2”. It also contains the empty sub-layers: Stops, Routes and Barriers. In the Network Analyst window, select the “Route 2” and click the “Route Properties” button. Turn to the tab of “General”, and change the Layer Name to “Yellow Flag”.

Figure 3.17. Removing the selection on the stop

Figure 3.18. Executing “Find the First Path” model
Figure 3.19. Script for executing “Find the First Path” model

Figure 3.20. Output of “Find the First Path” model
Yellow flags can be added onto the “Yellow Flag” route analysis layer and displayed on the map similar to the red flags. But the added yellow flags will not affect the routing of response vehicles that satisfy weight and height restrictions.

The routing of response vehicles and evacuees should be operated on two separate layers (or on different network datasets). On the layer used for routing response vehicles, only red flags are input as barriers, while on the layer used for evacuation operations, both red and yellow flags are identified as barriers and represented on the map. This concludes the steps for K-shortest path module. In the next chapter we will describe the multiple-stop routing module.

CHAPTER 4. MODULE FOR MULTIPLE-STOP ROUTING

The need for multiple-stop routing arises in situations when relief resources must be delivered to several locations using limited vehicles. As discussed in Chapter 2, if there is a particular order in which a single vehicle has to visit each location in a certain course, the problem can be viewed as sequence of shortest path problems between successive locations. If there is no such order for visiting stops, or if re-ordering is allowed, then the problem is more complicated. In these cases, the shortest path and corresponding travel cost between any given pair of locations has to be identified first, and the scheduling of delivery to each location forms a NP-hard problem. However, in the context of disaster relief operations, there are often some time window constraints, which reduce the solution space of this problem. In addition, in real-world operations, the number of stops to be routed through in a single round of delivery cannot be very large.

The ArcGIS Network Analyst can support multiple-stop routing in the same environment as the K-shortest paths routing discussed in Chapter 3. The associated procedures for initially establishing network dataset are discussed in section 3.2. An example of multiple-stop routing using ArcGIS Network Analyst is provided next.

4.1 Multiple-stop routing

Enable the ArcGIS Network Analyst according to steps 1–4 in section 3.3. Next, we illustrate the routing a response vehicle from a dispatch center to visit 3 stops.

A. Routing through ordered multiple stops

1. Click Stops(0) in the Network Analyst window, and click the “Create Network Location Tool” button on the

![Figure 3.21. Directions window](image1)

![Figure 3.22. Output of the second shortest path](image2)
Network Analyst toolbar. Then, first click the location of the dispatch center on the map as Stop 1, and click the stops to be visited on the map as Stop 2, Stop 3 and Stop 4 according to a given order (Figure 4.1). Click the “Solve” button on the Network Analyst toolbar to generate the optimal path through the stops according to the given order and the associated directions window, which provides turn-by-turn path details.

2. Considering a situation that link failure occurs on the generated path, click Barriers(0) in the Network Analyst window, and click the “Create Network Location Tool” button on the Network Analyst toolbar. Then, click the location of the reported link failure on the map and represent it using a red flag (here, we assume that the link failure occurs on the path between Stop 2 and Stop 3 as represented in Figure 4.3). After the barrier is added, click the “Solve” button on the Network Analyst toolbar to re-generate the optimal path.

B. Routing through multiple unordered stops

If there is no fixed order for visiting stops, or if re-ordering is allowed, the setting in the Network Analyst can be appropriately modified for the problem context.

1. Assume that the locations of the stops as in section 4.1.A. Click the “Route Properties” button at the upper-right corner of the Network Analyst window. In the prompted dialog box, check “Reorder Stops To Find Optimal Route”. Here, we also check “Preserve First
Figure 3.25. Adding the barrier (red flag) to identify link failure on the map

Figure 3.26. Output of re-routing based on the updated network
Stop” as we define Stop 1 as the dispatch center for the response vehicle.

2. Click “OK” to close the dialog box and click the Solve button on the Network Analyst toolbar to generate the optimal path.

If we compare these routes with the non-order visiting stops, we can observe that the original Stop 4 (see Figure 4.3) is visited first and is designated now as Stop 2. Similar changes are also applied to the other two stops.

4.2 Multiple-stop routing with time window constraints

When time windows constraints are to be imposed on some stops, the associated issues can be addressed by ArcGIS Network Analyst as follows:

1. Assuming the locations of the stops in A are applied. Click the “Route Properties” button at the upper-right corner of the Network Analyst window. In the prompted dialog box, check “Use Time Windows”. Also, check “Start Time” (a default start time 8:00:00 AM is provided by the system). In addition, we preserve the setting of allowing reordering. Then, click “OK” to close the dialog box.

2. Let us assume that there is a time window constraint imposed on Stop 2. Double-click the icon of Stop 2 in the Network Analyst window. It will open a message box containing the properties of Stop 2. Add the time window to the Value of “TimeWindowStart” and “TimeWindowEnd”. In Figure 4.7, we assume a time window from 8:00:00 AM to 8:05:00 AM.

3. Click “OK” to close the message box and click the “Solve” button on the Network Analyst toolbar to generate the optimal path.

Compare the result with the one obtained from B. Because of time window constraints on Stop 2, it is still visited first, while reordering is performed for Stop 3 and Stop 4. Also, it should be noted though Stop 2 is visited first, there is an inevitable violation to the time window based on the given traffic conditions. The
Figure 3.28. Adding a yellow flag to the map

Figure 4.1. Adding the multiple stops to route analysis layer
violation is marked on Stop 2 as a red square. Double-click the icon of Stop 2 in the Network Analyst window. From the message box of its properties, we can see that the status is shown as “Time window violation”. In this example, relief resources will be delivered to Stop 2 at 8:05:32 AM (as indicated by the Value of “ArriveTime” in the message box in Figure 4.9), a violation of 32 seconds.

Figure 4.2. Output of the optimal path for multiple-stop routing
CHAPTER 5. CONCLUSIONS

5.1 Summary

The primary objective of this study is to develop modules which assist INDOT in the routing operations of response vehicles and evacuees in a disaster. According to the characteristics of the routing problem...
in the context of disaster management, two modules of the specified functionalities are developed as deliverables to the relevant divisions in the INDOT:

1. The module of K-shortest paths routing: The identification of the K-shortest paths between an O–D pair is required for the routing of both response vehicles and evacuees. The developed module provides the functionality to generate K-shortest paths based on the given network conditions, and the generated paths are mostly distinct. That is, the generated paths do not share a significant proportion of common links.
2. The module of multiple-stop routing: In situations where relief resources need to be delivered to several locations (stops) using one or a limited number of response vehicles, this module supports the shortest path routing across multiple stops. This is critical in disasters when there is a priority associated with the stops to be visited, or there are time constraints for the delivery of relief resources at some stops. In such situations, any violations of time windows are indicated so that the operators can further re-arrange the fleet. If no priority of deliveries to the stops is imposed, the module can support re-ordering to achieve the shortest travel time.

Examples are provided for applying these two modules and performing routing operations in a post-earthquake situation. These modules can facilitate the routing operations in a broad range of disaster types like flooding, hazardous material spills, etc.

5.2 Contributions

The major contributions of this work are in development of the two routing modules which can work directly on ArcGIS software, the GIS platform employed in INDOT and IDHS for the associated operations, especially in terms of the K-shortest paths routing, which is not supported by the current version of the software. In addition, the network dynamics can be incorporated using a simple flag representation on the integrated GIS platform, enabling the operational framework as in Figure 1.1 to be realized in practical implementation.

5.3 Future research

This effort primarily addresses the problem of response operations, that is, efficient routing of response vehicles and evacuees by identifying strategic routes under dynamic network conditions. In terms of the operations of response vehicles, future efforts can entail the development of a platform which integrates vehicle routing and inventory management into a single decision support system for coordinating logistics in disaster management. Additionally, spatial analysis for disaster management problems may be necessary to demarcate the affected area into a number of operational zones, which may be different from the conventional traffic analysis zones. Such a zoning strategy may be more operationally effective in addressing the locations of dispatch centers for response vehicles and supply centers for disaster management.
From the perspective of evacuation operations, the modules developed in this study facilitate the determination of evacuation routes. However, for practical deployment, there are several other issues that ought to be addressed, such as the identification of evacuation area, location of shelters, and the coordination of different institutional management structures.

CHAPTER 6. EXPECTED BENEFITS & DELIVERABLES

The deliverables of this study include the proposed modules for K-shortest paths routing and multiple-stop routing. The modules can be directly used in the INDOT’s GIS system for practical implementation. Three electronic files and a hard copy of step-by-step operations manual for using the modules will be delivered. The electronic deliverables are:

- Folder “Data Layer”, which contains all the required layer files on Indianapolis area for this project.
- Project file “Project_Indy” (.mxd), which defines the environment in ArcMap for this project.
- Toolbox file “Network Model” (.tbx), which contains the models developed using geoprocessing tools in ArcToolbox

These modules can be directly transferred through email or any electronic media. A user manual that illustrates the execution of the K-shortest paths routing module is also provided along with the listed items.

Once the K-shortest paths module is installed, the multiple-stop routing operation can be implemented according to the steps illustrated in Chapter 4. The modules are expected to benefit the relevant agencies in identifying routes for disaster response operations. In addition, the GIS-based operability of the modules allow the integration with INDOT infrastructure monitoring system, so as to support re-routing operations due to possible link failure under disasters. Through the user-interface provided by the ArcGIS software, the graphic displays on the map layers can provide the ability for spatial visualization for the emergency response operators.

REFERENCES


Transportation Research Record, 2089, 18–25, doi: 10.3141/2089-03.
APPENDIX, STEP-BY-STEP MANUAL FOR OPERATING THE MODULES

“DYNAMIC REAL -TIME ROUTING FOR EVACUATION RESPONSE PLANNING”

Joint Research Transportation Program
Project No. C-36-17AAAA
File No. 8-4-79
SPR-3222

This document provides a step-by-step procedure to guide the user on how to add the K-shortest path routing module to ArcGIS project.

Step 1: Save the folder “Data Layer”, project file “Project_Indy” (.mxd) and toolbox file “Network Model” (.tbx) to a preferred location in the drive.

Step 2: Open ArcMap and open the project file “Project_Indy”.

Step 3: Right click on KSP or any other data layer in the window of active data maps. Then, point to “Data” and select “Repair Data Source…” Locate to the folder “Data Layer” and choose the corresponding shapefile (.shp).

One can also employ the module in an existing ArcGIS project comprising different data layers other than the Data Layer delivered with the study. However it needs the following files to be added to the project:

- **KSP**: It can be added by clicking “Add Data” button, going to the folder “Data Layer” and choosing KSP.shp.
- **Majorroad (and the associated network dataset)**; which is the data layer of roadway system.
- In order to apply the module to another roadway system, three attribute fields for the data layer are required. These are “Miles”, “Speed” and “TT”, which denote length (in miles), speed and travel time (in minutes) on a road segment (link).

Open attribute table of the roadway data layer, click “Options” and select “Add Fields…” to increase these three fields. Right click on the fields, select “Properties” to set

“One can also employ the module in an existing ArcGIS project comprising different data layers other than the Data Layer delivered with the study. However it needs the following files to be added to the project:

- **KSP**: It can be added by clicking “Add Data” button, going to the folder “Data Layer” and choosing KSP.shp.
- **Majorroad (and the associated network dataset)**; which is the data layer of roadway system.
- In order to apply the module to another roadway system, three attribute fields for the data layer are required. These are “Miles”, “Speed” and “TT”, which denote length (in miles), speed and travel time (in minutes) on a road segment (link).

Open attribute table of the roadway data layer, click “Options” and select “Add Fields…” to increase these three fields. Right click on the fields, select “Properties” to set

“Type” in Double, and select “Field Calculator” to specify the values of links (use TT = Miles / Speed * 60). After these changes, the associated network dataset also needs to be rebuilt using ArcCatalog (as shown in Chapter 3 of the project report).

Network Analyst and ArcToolbox are pre-set in “Project_Indy”. The figure below illustrates the Network Analyst and ArcToolbox...
windows. If these window are ready and appears in the workspace, one can directly go to Step 7; otherwise, users are required to go through Steps 4 to 7.

- **Step 4:** Click “Tools” in the toolbar and select “Extensions” from the menu. From the Extensions dialog box, check “Network Analyst” to enable it.
- **Step 5:** Click “View” in the window menu, point to “Toolbars”, and check “Network Analyst” to add the toolbar of Network Analyst to the current display.
- **Step 6:** Click the “Network Analyst Window” button on the Network Analyst toolbar, and deck the Network Analyst window to the current display.
- **Step 7:** Click the “Show/Hide ArcToolbox window” button to open the ArcToolbox window, and deck the window to the current display.
- **Step 8:** Right-click ArcToolbox and select “Add Toolbox...”. Locate to the folder where the file “Network Model” is saved and add this file to the toolbox of the current project.
- **Step 9:** The toolbox “Network Model” is added under ArcToolbox. Expand the “Network Model toolbox”, which contains the three developed models: “Find the First Path”, “Find the Next Path” and “Dataset Recover”.

Due to the relocation of files or while transferring the files, it is at times possible that the linkage between the developed models and the associated files may be lost. The following steps should be used to check for the loss of linkages and to re-build the models.

- **Step 10:** Rebuild the file linkage for “Find the First Path” model.
- **Right-click** the “Find the First Path” model and select “Edit...” to open the diagram of model procedure. Zoom to the full extent of the procedure by clicking “Full Extent” button, and adjust to a preferred extent using “Zoom In” and “Pan” buttons. If the procedure is not properly aligned, click “Auto Layout” button to fix it. The same actions may be needed for the other two models: “Find the Next Path” model and “Dataset Recover” model.
If one of the yellow boxes (except the Solve box) connect to a blue ellipse(s), it implies the linkage needs to be rebuilt. Double click on each box to open its setting window.

For the input of “Target Dataset”, click the “Open” button and go to the folder where KSP.shp is saved. Select the KSP file to rebuild the linkage.

Step 11: Rebuilding the file linkage for “Find the Next Path” model.
Right click on “Find the Next Path” model and select “Edit” to open the diagram of the model procedure as illustrated hereafter.
For the input of “Input Feature Layer”, click the “Open” button and go to the folder where Majorroad.shp is saved. Select the Majorroad file to rebuild the linkage.

For the input of “Input Network Dataset”, click the “Open” button and go to the folder where Majorroad_ND.nd is saved. Select the Majorroad file to rebuild the linkage.

Step 12: Rebuild the file linkage for “Dataset Recover” model.
For the input of “Input Table”, click the “Open” button and go to the folder where Majorroad.shp is saved. Select the Majorroad file to rebuild the linkage.
For the input of “Input Network Dataset”, click the “Open” button and go to the folder where Majorroad_ND.nd is saved. Select the Majorroad file to rebuild the linkage.

For the input of “Input Rows”, click the “Open” button and go to the folder where KSP.shp is saved. Select the KSP file to rebuild the linkage.