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Final Report

**CRITICAL ROUTE NETWORK FOR
EARTHQUAKE RESPONSE AND
DYNAMIC ROUTE ANALYSIS**

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Critical Route Network for Earthquake Response and Dynamic Route Analysis

Introduction

In the JTRP-funded study “Emergency Earthquake Routes for the State of Indiana; Part I: Criteria for Selection of Primary Routes: Transportation Aspects,” a multi-commodity maximal covering network design formulation based optimization methodology was proposed to identify a critical routes sub-network for the Indiana component of the Wabash Valley Seismic Zone in the INDOT Vincennes District. Addressed from a planning perspective, the primary objective was to strengthen the bridges on this sub-network through an effective seismic retrofit scheme so as to increase the likelihood of the critical routes being available to first responders following an earthquake to maximize response effectiveness. The proposed methodology was motivated by the need to consider the key factors for effective earthquake response in a single framework. This was done by first defining the concept of “critical routes.” The critical routes of a transportation network are the set of routes whose functionality is critical to the effectiveness of earthquake response, or equivalently, the routes that provide the quickest response (least travel time) to most of the population (maximal coverage).

The above study considered all Interstates, US Roads and State Roads in identifying the critical routes sub-network that should be seismically strengthened. However, Part II of that study “Route Seismic Vulnerability Aspects,” which addressed the bridge seismic retrofit aspects, considered only the sub-network corresponding to the National Highway System and the National Truck Network in identifying the bridges for retrofit. The current study seeks to analyze whether the sub-network corresponding to the National Highway System and the National Truck Network compares well, from a costs-benefits perspective, to that suggested by the previous study (Figure 6.1 of Part I Report). Hence, a key objective of the current study is from a planning perspective.

The second objective of the current study is in the operational context. It aims to determine a methodological framework for dynamically rerouting first responders when part of a route is unavailable due to the earthquake. This objective provides back-up operational response plans when specific road segments of the recommended critical routes sub-network fail during an actual earthquake.

Findings

In the context of the first objective, the study found that the performance of the sub-network consisting of the National Highway System and the National Trucking Network is dominated by that of the more complete network used in the Part I Report of the previous study. This is illustrated by Figure 3.4 in the Draft Final Report of the current study. This is because the sub-network considered in the current study has lesser connectivity compared to the more

complete network. That is, the more complete network offers better ways of connecting the major population centers with lesser cost.

The study also led to a few specific insights for decision-makers. The high capacity infrastructure associated with the National Highway System and the National Trucking Network can respond better under post-earthquake high-volume scenarios associated with passenger and cargo movement in the medium-

term. Also, its performance tends to increase when greater weight is provided to population coverage under the lower budget levels. However, as stated above, the more complete network based solution tends to dominate under low volume emergency response operations immediately after an earthquake; a wider range of routing options is available at lower retrofitting costs.

For the second objective, a methodological framework (operational flowchart Figure 4.1) was developed for dynamically updating the critical routes sub-network based on the surviving network after an earthquake. A software application was developed for implementing it for real-time operations. Before an earthquake, the network topology static database is maintained up to date, and represents the current network. Also, the network status dynamic database is initialized by specifying all links to be in unverified availability status. After

an earthquake, the optimization component calculates the optimal routes considering the current network status. Then, the component responsible for verifying the availability status of the links used in the proposed routes will identify which links in the proposed routes have not been verified. If unverified links exist, they are made known to the decision-making agency. The agency is responsible for verifying the actual availability status of these links after the earthquake and then updating the network status dynamic database accordingly. After the dynamic database is updated, the new optimal critical routes sub-network is generated. The links in the updated sub-network with unverified availability status are verified by the agency. This procedure continues until the availability status of all links in the latest updated sub-network has been verified. Then, the optimal verified routes are made available.

Implementation

(1) The performance of the INDOT administered network (National Truck Network, National Highway System) is compared with that of the original critical routes network recommended in Part I of the SPR 2480 Final Report. This provides directions for choosing the final earthquake

critical routes sub-network. (2) A dynamic re-routing methodological framework has been developed. A User Manual is provided for implementing it using the GAMS/CPLEX optimization software.

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16. Abstract <p>Earthquakes can significantly disrupt societal functioning, cause ecological damage, and lead to loss of human lives and property, warranting a coordinated and efficient response to mitigate their negative impacts. Preparedness against earthquakes entails a pre-disaster planning aspect and a post disaster operational aspect. In the JTRP study "Emergency Earthquake Routes for the State of Indiana; Part I: Criteria for Selection of Primary Routes: Transportation Aspects", a multicommodity maximal covering network design formulation based optimization methodology was proposed to identify a critical routes sub-network for the Indiana component of the Wabash Valley Seismic Zone in the INDOT Vincennes District. Addressed from a planning perspective, the primary objective was to strengthen the bridges on this sub-network through an effective seismic retrofit scheme so as to increase the likelihood of the critical routes being available to first responders following an earthquake to maximize response effectiveness. The critical routes of a transportation network are the set of routes whose functionality is critical to the effectiveness of earthquake response, or equivalently, the routes that provide the quickest response (least travel time) to most of the population (maximal coverage).</p> <p>The above study considered all Interstates, US Roads and State Roads in identifying the critical routes sub-network that should be seismically strengthened. However, Part II of that study "Route Seismic Vulnerability Aspects", which addressed the bridge seismic retrofit aspects, considered only the sub-network corresponding to the National Highway System and the National Truck Network in identifying the bridges for retrofit. Hence, the first objective of the current study is to analyze whether the sub-network corresponding to the National Highway System and the National Truck Network compares well, from a costs-benefits perspective, to that suggested by the previous study. The second objective, which arises in the operational context, aims to determine a methodological framework for dynamically rerouting first responders when part of a route is unavailable after an earthquake. It provides back-up operational response plans when specific road segments of the recommended critical routes sub-network fail during an actual earthquake.</p>			
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CHAPTER 1. INTRODUCTION

1.1 Background and motivation

Earthquakes can significantly disrupt societal functioning, cause ecological damage, and lead to loss of human lives and property, warranting a coordinated and efficient response to mitigate their negative impacts (Peeta and Viswanath, 2004). Past experience with earthquakes has demonstrated the vulnerability of the critical infrastructural lifelines and the need for mitigation strategies as well as emergency response planning. Preparedness against earthquakes includes a pre-disaster planning aspect and a post disaster operational aspect.

In the INDOT-funded study “Emergency Earthquake Routes for the State of Indiana; Part I: Criteria for Selection of Primary Routes: Transportation Aspects” (SPR-2480), Peeta and Viswanath (2004) developed a methodology to address the problem from a planning perspective. It enabled the decision-makers to identify an effective seismic retrofit scheme vis-à-vis earthquake response for the bridges of a network. The methodology was motivated by the need to consider the key factors for effective earthquake response in a single framework. This was done by first defining the concept of *critical routes*. *The critical routes of a transportation network are the set of routes whose functionality is critical to the effectiveness of earthquake response, or*

equivalently, the routes that provide the quickest response (least travel time) to most of the population (maximal coverage) among all major population centers.

The critical routes problem in the previous INDOT study led to a network approach with multiple origin-destination (O-D) pairs, labeled the Multi Commodity Maximal Covering Network Design Problem (MCMCNDP). Its objectives are to minimize the routing costs over all O-D pairs and maximize the total population covered, subject to a budget constraint based on the fixed costs incurred on the chosen links. As mentioned earlier, the MCMCNDP represents the planning aspect of identifying the bridges to seismically retrofit by factoring the transportation performance aspects in determining the critical routes.

In an operational context following an earthquake, first responders seek to reach the affected population in the least time possible. This problem is classified as a multi-commodity uncapacitated shortest path problem, which is decomposed to multiple single shortest paths. Extensive literature exists on solution algorithms for the shortest path problem (Ahuja et al., 1993). Nevertheless, the key issue is that the status of the network, in terms of whether a link is accessible or inaccessible due to severe seismic damage, is unknown.

The unknown state of the network in the aftermath of an earthquake generates two major problems. First, the feasibility of a proposed route is not guaranteed since it may contain inaccessible links leading to delays in first response operations. Second, the time to acquire the information on the status of the entire network is critical for on-time deployment; this can be a time consuming task. Interestingly, it is not necessary that the

status of every link in the network has to be known. If just the sub-network that provides the shortest paths is examined, then the quickest feasible deployment of first responders can be achieved.

1.2 Study objectives

This study has two objectives. The first objective has a planning perspective while the second objective has an operational perspective.

The first objective is to analyze the performance of the network shown in Figure 4.5 of Part II of SPR-2480 Final Report (shown in Figure 1.1 of this report) in terms of earthquake response planning, compared to the performance of the network shown in Figure 6.1 of Part I of SPR-2480 Final Report (shown as Figure 1.2 here).

Currently, the difference between the route networks shown in Figures 1.1 and 1.2 is that the former network corresponds to routes that belong to the National Truck Network and the National Highway System, and are maintained by the Indiana Department of Transportation, hereafter called the INDOT-Maintained Network (IMN). The latter considers all Interstates, US Roads and State Roads in the vicinity of Vincennes District of southwest Indiana, hereafter called the Complete Road Network (CRN). The IMN is a sub-network of the CRN.

In the INDOT-funded project SPR-2480, the MCMCNDP had been applied to the CRN. However, the CRN includes road segments which are maintained either by INDOT or by other local authorities. In this study, the MCMCNDP will be applied to the IMN so as to compare its performance to that of the CRN.

The results will be analyzed using the format of Figure 6.1 of SPR-2480 (indicated as Figure 1.3 here), which shows the non-inferior solution fronts. A non-inferior solution front is the curve of those solutions for which the best performance level of the second objective (maximum population coverage) is achieved (as shown in Figure 1.3) for a given performance level of the first objective (least travel time).

The second objective is to determine a methodological framework to dynamically reroute first responders when part of a route is unavailable due to the earthquake. This objective provides back-up operational response actions when specific road segments of the recommended primary route network fail during an actual earthquake.

1.3 Organization of the research

The remainder of the research is organized as follows. Chapter 2 provides an improved formulation for the MCMCNDP. Chapter 3 identifies the IMN where the MCMCNDP will be applied, and compares the computational results to the computational results of the CRN in southwest Indiana (Peeta, Viswanath, 2004). In Chapter 4 the problem of dynamic rerouting of first responders from their bases to the affected population centers is defined. The methodological framework is analyzed, the corresponding formulation is provided and a computationally efficient solution methodology is developed. Chapter 5 summarizes the research and its contributions, and provides future research directions.

Figure 1.1. Suggested grid of the Earthquake Emergency Routes in the INDOT Vincennes District.

Figure 1.2. CRN of southwest Indiana.

Figure 1.3. Non-inferior solution set for different budget values in the CRN.

CHAPTER 2. AN IMPROVED FORMULATION FOR THE MCMCNDP

This chapter introduces an improved formulation for the MCMCNDP. Section 2.1 states the MCMCNDP. Section 2.2 addresses the key issues of the original formulation that increase the complexity of the formulation. Section 2.3 discusses how those issues are addressed in the improved formulation. Section 2.4 introduces the improved mathematical formulation. Section 2.5 summarizes the improved mathematical formulation.

2.1 *Problem statement*

The MCMCNDP is defined hereby. We are given the locations of demand population centers of a region and its associated undirected network. The network links have a fixed budgetary cost for their usage (bridge retrofitting) and a routing cost (travel time). There is a budget constraint on the total budgetary cost incurred. The MCMCNDP seeks to allocate a limited budget to retrofit links such that the total routing costs for a set of O-D pairs is minimized and the total demand covered by the routes connecting them is maximized. The demand of a center is covered if a link in one of the selected routes provides access to it.

2.2 Key issues in the original formulation

The original formulation had been an NP-hard integer formulation. Due to the intractable nature of the sub-tour elimination constraints, a significant part of the expected isolated sub-tours was handled by the valid inequalities and the rest of them were manually removed. This led to increased computational time due to a) manual or exogenous interference with another software, b) additional computations for each of the new exogenously identified sub-tours, till all sub-tours were eliminated. Finally, in the original formulation the set of variables handling a) the decision to retrofit a link and b) the population demand coverage, were binary and not linear. This increased the size of the branch-and-bound tree, thus affecting significantly the computational time.

2.3 Key issues in the improved formulation

In the proposed improved formulation, all tours are handled in a single compact formulation. The concept utilized to handle all sub-tours in the improved formulation is an extension of Wong (1980) sub-tour elimination technique used for the traveling salesman problem. The difference is that in the traveling salesman problem all nodes have to be connected in a single tour, while in the coverage problem not all nodes have to be in the “covering” path. A special variable identifying the existence of a node in a path is introduced along with the corresponding constraints. The mechanism is as follows. If an isolated tour exists then a set of nodes belonging to the tour is defined. For these nodes, an auxiliary flow, which is not allowed in unused paths of the main routing flow, can never be sent from the origin to the nodes of the isolated sub-tour, thus allowing no isolated-tour to exist.

Moreover, the integrality constraint for the set of variables handling a) the decision to retrofit a link and b) the population demand coverage, are linearly relaxed. The set of variables handling the decision to retrofit a link has a lower bound defined by the existence of commodity flow and an upper bound defined by the budget constraint. The set of variables handling the population demand coverage is bounded by unity since a population considered will be covered at most once.

The hereafter improved formulation addressed all sub-tours in a single computation step and it is a mixed integer formulation with a reduced number of binary variables.

2.4 Improved formulation

This section first describes the notation, parameters and decision variables, and then introduces the mixed integer programming formulation for the MCMCNDP.

2.4.1 Notation and parameters

Let $G(N, E)$ denote an undirected network with node set N and link set E . The indices i and j denote a node in the network, $i, j \in N$ and $E \subseteq N \times N$, where $[i, j]$ denotes an undirected link between nodes i and j with a nonnegative fixed cost f_{ij} . Let B to denote the available budget. Each O-D pair in the network is represented as a unique commodity type. Let k represent the commodity type index, $k \in K$, where K denotes the set of all commodities. One unit of flow of commodity k must be transported over the network from its origin $O(k)$ to its destination $D(k)$. To differentiate the

direction of flow of a commodity, we consider two directed links (i, j) and (j, i) corresponding to each original undirected link $[i, j]$. Let A denote the set of the directed links; all links are uncapacitated. Parameter b_i^k denotes whether node i is an origin, a destination or intermediate node for commodity k . If node i is an origin for commodity k then $b_i^k = -1$. If node i is a destination for commodity k then $b_i^k = 1$. If node i is an intermediate node for commodity k then $b_i^k = 0$.

Let c_{ij}^k be the nonnegative routing cost for a unit of commodity k on link (i, j) , and m the demand center index, $m \in M$, the set of demand centers in the region. Let r_m represent the demand associated with demand center m , and E_m the set of links that are eligible to cover it. The demand centers are treated separately from the nodes in the network, whereas past studies assign demand centers to a node in the network which is a more restrictive approach. Finally, the two objectives of total travel time and coverage, are including in a single weighted objective after being multiplied with weights u_1 and u_2 respectively.

2.4.2 Decision variables

The formulation contains five types of variables.

(i) The arc flow variables denoted by the vector $x = \{x_{ij}^k\}$, which define the flow of different commodities in each of the selected links. If there is a unit flow of commodity k on link (i, j) then $x_{ij}^k = 1$, otherwise $x_{ij}^k = 0$.

(ii) The design variables denoted by the vector $y = \{y_{ij}\}$, which define the links selected for the network design. If link $[i, j]$ is used in a flow path then $y_{ij} = 1$, otherwise $y_{ij} = 0$. In the improved formulation this set of variables is linearly relaxed because at optimality conditions it is either 0 or 1 strictly.

(iii) The coverage variables denoted by the vector $z = \{z_m\}$, which define whether or not a demand center is covered. If demand center m is accessible from a link of a flow path then $z_m = 1$, otherwise $z_m = 0$. In the improved formulation this variable is also linearly relaxed because at optimality conditions it is either 0 or 1 strictly.

(iv) The variables denoted by $v = \{v_i^k\}$, which define the number of times that a node is crossed from a path per commodity. They are modeled as linear variables because they are defined directly from the integral flow variables.

(v) The auxiliary flow variables denoted by the vector $w = \{w_{ij}^k\}$, which indicate the auxiliary flow routed to ensure connectivity among all nodes used in the path of commodity k , therefore ensuring that no isolated sub-tours exist. Those variables are also linear because they are only needed to establish connectivity.

2.4.3 The MCMCNDP formulation

The MCMCNDP formulation has two objectives: Z_1 , the total routing cost and Z_2 the total demand covered, where,

$$Z_1 = \sum_{k \in K} \sum_{(i,j) \in E} c_{ij}^k \cdot x_{ij}^k \quad \text{and} \quad Z_2 = \sum_{m \in M} r_m \cdot z_m .$$

The mixed integer programming formulation for the MCMCNDP is expressed as follows:

$$\text{Minimize:} \quad u_1 Z_1 - u_2 Z_2 \quad (2.1)$$

Subject to:

$$\sum_{(i,j) \in A} x_{ij}^k - \sum_{(j,i) \in A} x_{ji}^k = b_i^k \quad \forall i \in N, \forall k \in K \quad (2.2)$$

$$z_m \leq \sum_{k \in K} \sum_{[i,j] \in E_m} (x_{ij}^k + x_{ji}^k) \quad \forall m \in M \quad (2.3)$$

$$x_{ij}^k \leq y_{ij} \quad \forall k \in K, \forall [i,j] \in E \quad (2.4)$$

$$x_{ji}^k \leq y_{ij} \quad \forall k \in K, \forall [i,j] \in E \quad (2.5)$$

$$\sum_{[i,j] \in E} f_{ij} \cdot y_{ij} \leq B \quad (2.6)$$

$$v_i^k = \frac{1}{2} \left(\sum_{(i,j) \in A} x_{ij}^k + \sum_{(j,i) \in A} x_{ji}^k + |b_i^k| \right) \quad \forall i \in N, \forall k \in K \quad (2.7)$$

$$v_i^k \leq 1 \quad \forall i \in N, \forall k \in K \quad (2.8)$$

$$\sum_{(i,j) \in A} w_{ij}^k - \sum_{(j,i) \in A} w_{ji}^k = v_i^k \quad \forall i \in N, b_i^k = 0, \forall k \in K \quad (2.9)$$

$$\sum_{(i,j) \in A} w_{ij}^k - \sum_{(j,i) \in A} w_{ji}^k = - \sum_{i \in N, b_i^k = 0} v_i^k \quad \forall i \in N, b_i^k = -1, \forall k \in K \quad (2.10)$$

$$w_{ij}^k \leq (|N| - 2) \cdot x_{ij}^k \quad \forall k \in K, \forall [i,j] \in E \quad (2.11)$$

$$y_{ij}^k \leq 1 \quad \forall k \in K, \forall [i,j] \in E \quad (2.12)$$

$$z_m \leq 1 \quad \forall m \in M \quad (2.13)$$

$$y_{ij}^k, w_{ij}^k \geq 0 \quad \forall k \in K, \forall [i, j] \in E \quad (2.14)$$

$$z_m \geq 0 \quad \forall m \in M \quad (2.15)$$

$$v_i^k \geq 0 \quad \forall i \in N, \forall k \in K \quad (2.16)$$

$$x_{ij}^k \in \{0, 1\} \quad \forall k \in K, \forall [i, j] \in E \quad (2.17)$$

Constraint (2.2) is the conservation of flow for all commodities and nodes. Constraint (2.3) allows a population center to be covered only if there is a commodity flow in the adjacent links. Constraint (2.4) and (2.5) do not allow routing in a link, unless it has been retrofitted. Constraint (2.6) is the total budget constraint.

The new constraints added for handling the isolated sub-tours are constraints (2.7)-(2.11). Constraint (2.7) defines how many times a node is crossed in the path of a commodity, and constraint (2.8) ensures that this node is crossed at most once per commodity. This constraint ensures that sub-tours attached to the main path do not exist. Constraint (2.9) makes each crossed node a destination node for the auxiliary flow ensuring connectivity (therefore eliminating sub-tours) and constraint (2.10) indicates the total amount of auxiliary flow sent from the origin of each node to all other intermediate nodes for ensuring the conservation of the auxiliary flow. Constraint (2.11) restricts auxiliary flow only to the links that the main flow (response vehicles) has been routed.

Constraints (2.12) and (2.13) are the upper linear bound of the previously binary variables. Constraints (2.14) to (2.16) are the non-negativity constraints for the linear variables and constraint (2.17) is the integrality constraint for the flow variables.

2.5 Discussion

In this chapter the MCMCNDP was stated. Key issues of the original formulation were identified considering the set of sub-tour elimination constraints and the number of integer variables. The improved formulation for the MCMCNDP addresses these issues by a) directly eliminating all sub-tours in a single computation step, and b) reducing the number of binary variables by applying the appropriate linear relaxations. The improved formulation is used for the IMN.

CHAPTER 3. CASE STUDY: THE IMN

Chapter 3 studies the IMN. This chapter discusses the application of the MCMCNDP formulation to the determination of critical routes for earthquake response in southwest Indiana. It describes the details of the case study, followed by a summary of the solution procedure and its implementation. In Section 3.1 the IMN is described. In Section 3.2 implementation details for both the CRN and IMN are discussed. In Section 3.3 the computational results are presented. A concluding discussion is provided in Section 3.4.

3.1 IMN in SPR-2480

The IMN in SPR-2480 consists of the following road segments, as shown in Figure 1.1:

- US-41 from Terre Haute south to Evansville and the Kentucky border (Ohio River).
- SR-67 from Freedom to SR-57 junction and SR-57 from SR-67 to I-64.
- I-164 from I-64 to US-41.
- US-231 from SR-54 at Bloomfield south to Rockport and to Kentucky border (Ohio River).

- SR-37 from Bloomington south to SR-237 and SR-237 to Cannelton and the Kentucky border (Ohio River).
- SR-154 from Illinois border (Wabash River) to US-41, and SR-54 from US-41 east to SR-45.
- US-50 from Illinois border (Wabash River) at Vincennes east to SR-446 east of Bedford.
- SR-64 from Illinois border (Wabash River) to Princeton to US-41.
- I-64 from Illinois border (Wabash River) to SR-66 at Carefree.
- SR-57 from US-41 past Evansville Airport to I-164.
- SR-62 from Illinois border (Wabash River) through Evansville to US-231.
- SR-66 from US-41 east to Rockport.

3.2 Implementation details

The implementation details refer to: (i) modifications to the IMN and the CRN (Section 3.2.1), (ii) the numerical selection of the objective function weights (Section 3.2.2), and (iii) the usage of bridge deck surface as a proxy for bridge retrofit budget (Section 3.2.1).

3.2.1 Network modifications

A detailed examination of the IMN and the CRN of the previous study, SPR-2480, indicate that some modifications are necessary to both networks to ensure that they

can be compared in a consistent manner. We discuss these modifications hereafter and finalize the networks used for the analysis in this study.

The CRN does not include two road segments of SR-37, which exist in the IMN. These are: (i) the road segment of SR-37 from Bedford south to Paoli, and (ii) the road segment of SR-37 from SR-64 south to I-64 (Figure 3.1). These two segments are now added to the CRN.

The northern border of the original IMN, which is south of I-70, is substantially more south than the northern border of the original CRN, which is US-40. The implication is that many population centers which had been considered in SPR-2480 as part of the CRN (including the major population centers of Terra Haute, Brazil, and Greencastle) cannot be considered in the IMN in terms of population coverage or in terms of routing connectivity. This is now modified by adding to the IMN: (i) the road segment of I-70 from Illinois border to Cloverdale and (ii) the road segment of US-231 from Spencer to Greencastle. The modifications are indicated in Figure 3.2.

As the IMN is a sub-network of CRN, it does not have some of the links present in the CRN. This requires the population to be redistributed to only these links present in the IMN so as to cover the entire population using just the IMN. These population centers are now reassigned to their closest road links in the IMN. This implementation detail also makes population coverage easier to achieve in the IMN.

The aforementioned network modifications define the IMN and the CRN for this study, as shown in Figure 3.3. The parameters of the resulting transportation networks are

indicated in Appendices A, B and C. The parameters of the population centers are indicated in Appendices D and E.

3.2.2 Objective function weights

The IMN considers two different objectives: travel time and coverage, under a limited budget constraint. These objectives do not necessarily move in the same direction. That is one may improve while the other deteriorates for a given solution in terms of bridge retrofit. Hence, trade-offs exist between these two objectives. From a practical standpoint this aspect is addressed by assigning different weights to these two objectives to indicate different levels of importance for each of them. This implies that the decision maker can select the level of importance given to each objective. Based on this perspective, the following pairs of weights (u_1 for travel time, u_2 for coverage) were considered: (0.999,0.001), (0.995,0.005), (0.990,0.010), (0.9825,0.0175), (0.975,0.025), (0.9500,0.0500) and (0.900,0.100). The numerical value of the weights indicate the relative importance given to travel time and population coverage.

3.2.3 Bridge deck surface as a proxy for bridge seismic retrofit budget

The budget for bridge earthquake retrofitting is measured in terms of millions of square feet of bridge deck surface. The bridge deck surface is used as a proxy for the actual retrofitting costs which are not available. The problem is solved for budgets ranging from 1.67 million square feet of bridge deck (which is the least retrofitting investment for establishing connectivity among all major population centers) to 3.33

million square feet (beyond which the marginal benefit of the investment is minimal) in increments of 0.33 million square feet of bridge deck surface.

3.3 Computational results and analysis

The numerical results for both the IMN and the CRN are illustrated in Figure 3.4 and provided in Appendix F. The following observations compare the performance of these two networks.

The CRN performs better in terms of travel time (lower travel times) for greater weights on the travel time criterion. This is due to the increased spatial solution space of the CRN (more links to select from, more available paths). The straightforward practical implication is that the CRN is better for first responder operations, when minimization of the response time is the sole objective. It is also noted here that for the low traffic volume of response operations, the IMN which, consists of multi-lane (greater deck) bridges, is less efficient to retrofit. The reverse is true when the high traffic volumes associated with the IMN are factored in. That is, the decision to retrofit almost all links of the IMN (as illustrated in Figures 3.6 to 3.11) is implied when the high daily volumes of traffic on the IMN links are accounted too. While this study (and SPR-2480) addresses only the earthquake response planning objectives, in reality, the day-to-day traffic volumes and their implied link capacities should be a bigger factor in identifying the critical links to retrofit.

The CRN provides greater flexibility to the decision maker as it has a lot more links from which to choose the critical link. Thereby, it has a greater total travel time range, from 1320 to 1780 minutes, while the IMN ranges from 1580 to 1750 minutes.

The CRN has population coverage values ranging from 407,000 to 457,000 when the IMN ranges from 432,000 to 452,000.

The budget percentage required for retrofitting links of the CRN that belong to the IMN is very high (Figure 3.5). This indicates once more the expensive nature of IMN infrastructure, which is reasonable when the daily traffic volumes on them are factored into the decision making process by the traffic agency.

3.4 *Discussion*

In this chapter, the IMN was identified and correlated to the CRN of seismic-prone southwest Indiana. The computational results indicated that the CRN provides a more flexible performance space for the decision makers due to its spatial extent and achieves greater globally optimum values (minimum travel time of 1320 minutes , maximum population coverage of 457.000) (Figure 3.4). Furthermore, the IMN has a necessary and dominating seismic retrofitting cost, even if considered as part of the CRN (Figure 3.5).

Concluding, the CRN performs better for the low volume emergency response operations since it provides a wider range of routing options (more road links) at a lower cost because it can avoid the retrofitting of the costly multi-lane INDOT maintained infrastructure. On the other hand, it is the IMN's high capacity infrastructure which can resume the post-earthquake high-volume and day-to-day industrial, cargo, commercial and commuting traffic volumes at regional, state and federal level.

Figure 3.1. Two road segments of SR-37 existing in the IMN that are added to the CRN.

Figure 3.2. Modification of the northern border of the IMN (shown using the thick highlight).

Figure 3.3. The CRN (all links) and the IMN (highlighted links).

Figure 3.4. The set of non-inferior solutions for IMN and CRN.

Figure 3.5. Percentage of the budget required for the CRN that belongs to the IMN.

Figure 3.6. Critical routes for the weight pair (0.999, 0.001) and budget 1.67 million sq. feet in the IMN.

Figure 3.7. Critical routes for the weight pair (0.990, 0.010) and budget 2.00 million sq. feet in the IMN.

Figure 3.8. Critical routes for the weight pair (0.999, 0.001) and budget 2.00 million sq. feet in the IMN.

Figure 3.9. Critical routes for the weight pair (0.990, 0.010) and budget 2.33 million sq. feet in the IMN.

Figure 3.10. Critical routes for the weight pair (0.983, 0.017) and budget 2.63 million sq. feet in the IMN.

Figure 3.11. Critical routes for the weight pair (0.995, 0.005) and budget 3.33 million sq. feet in the IMN.

CHAPTER 4. DYNAMIC REROUTING

Chapter 4 studies the problem of dynamically rerouting first responders or traffic for arbitrary scenarios or actual events, identified by INDOT, where part of a route is unavailable due to the specific earthquake characteristics. This objective provides back-up operational response actions when specific road segments of the recommended primary route network fail.

In Section 4.1 the methodological framework is defined and the components of the methodological framework are described. In Section 4.2 the operational flow chart is summarized. In Section 4.3 the mathematical formulation of the corresponding optimization problem is modeled. In Section 4.4 the solution methodology is described. The chapter ends with a concluding discussion in Section 4.5. The GAMS/CPLEX optimization software is used to calculate the dynamic routes, for which internet resources, code and the user manual is provided in Appendices G, H and I.

4.1 Methodological framework

The problem of dynamically rerouting vehicles in a network with unknown link availability status can produce an arbitrarily large number of scenarios, each corresponding to the combination of different availability statuses among all links in the network. Since this number grows exponentially, the number of potential scenarios

becomes prohibiting for operational applications. It is estimated that even if all scenarios have been pre-calculated and saved efficiently in an electronic format, the access time at the time needed will still be non-trivial. On the contrary, compared to the time accessing a large database, the computational time for the framework proposed is considered to be significantly lower, thus more efficient for real-time operations. It is noted that the key characteristic of the problem is that the final status of the links in the network is unknown until the actual earthquake event. Only after part of the network status has been verified, exact routing operations become available.

The methodological framework consists of 6 components: 1) a static database for storing the network topology, 2) a dynamic database for storing and updating the network status, 3) the optimization component responsible for calculating and proposing the dynamic routes, 4) the verification of the availability status of the proposed routes, 5) the updating of the dynamic network status database for the case that certain links in the proposed routes have not been verified, and 6) the final verified dynamic routes.

4.1.1 Network topology static database

In the network topology static database, the road network before the earthquake is stored. It contains the set of nodes defining the network and the set of links with their travel times. Those data are considered to be known before the event of an earthquake, therefore they do not need to be updated after the event of the earthquake. This database has to be updated only when new links are constructed or have been considered abandoned.

4.1.2 Dynamic network status database

In the dynamic network status database, the status of the road network after the earthquake is stored. It contains 2 parameters for each link, one defining the link status and one defining whether the link has been verified. Initially, it is considered that all links are available and that their status has not been verified. This initialization is selected because the first proposed paths are simply the shortest paths of the initial pre-earthquake network. Then only the unverified links on the proposed routes will have to be verified. This process helps responders to focus strictly on verifying the availability of the links in the optimal routes only, rather than spending precious response time trying to verify the status of links that will not be included in the optimal routes. It is highlighted that the dynamic database has to be initialized before every mock or actual earthquake response operation as previously described. Finally, in the case that certain links are not available for response operations before the event of the earthquake (due to major maintenance works or other accidents and events), they can be defined in the dynamic network status database as non-available and verified.

4.1.3 Optimization component

The optimization component is responsible for calculating the optimal routes given the network status. The optimization component does not identify whether the proposed routes are including links whose status has not been verified. As will be described in later sections, the multi-commodity uncapacitated shortest path problem is solved, which is decomposed to multiple shortest paths. Very efficient algorithms exist

for the shortest path problem which is solved multiple times in a short time duration. The CPLEX optimization software is used.

4.1.4 Proposed route verification component

The route verification component is responsible for verifying the status of the links in the proposed routes. If the status of a link(s) in the proposed route has not been verified, then an appropriate file output is generated that asks the controller to verify the availability status of the unverified link(s). If the status of all links in the proposed routes has been verified, then the optimal verified routes are released.

4.1.5 Network status update

This component corresponds to the set of actions necessary for identifying the status of unverified links and inserting this information in the dynamic network status database. There are two pieces of information that are updated: a) the link verification status, which changes from unverified to verified, and b) the link availability status which can either remain as is (available) or change to unavailable if the link is verified to be unavailable. When these pieces of information are updated, then the optimization component will be capable of calculating an updated optimal proposal.

4.1.6 Verified optimal routes

This component is the final output of the dynamic rerouting methodological framework. Only after all links in the updated optimal routes have been verified, will the process converge to the final output. The optimal routes are given in the form of an output file, where the route of each origin-destination pair is specified.

4.2 Operational flow chart

The operational flow chart of the proposed framework is illustrated in Figure 4.1 and summarized here.

Before an earthquake, the network topology static database is maintained up to date, thus realistically representing the current network. The network status dynamic database is updated by specifying the current availability status of all links and setting all links to be in unverified status.

Following an earthquake, the optimization component calculates the optimal routes considering the pre-earthquake network status. Then the component responsible for verifying the availability status of the links used in the proposed routes will identify which links in the proposed routes have not been verified. In the case that unverified links do exist, these links are made known to the controller. The controller is responsible for verifying the actual availability status of these links and then update the network status dynamic database accordingly. After the dynamic database is updated, the new optimal routes are calculated. The links in the proposed routes whose availability status has not been verified will have to be verified again by the controller. This process iterates till the availability status of all links in the proposed routes have been verified, and the optimal verified routes are made available.

4.3 Mathematical formulation

In this section the mathematical formulation for the optimal dynamic routes is described.

4.3.1 Problem statement

The problem of defining the optimal dynamic routes seeks the fastest routes from the location of first responders to the affected population centers given the availability of the used links.

4.3.2 Parameters

Let $G(N, E)$ denote an undirected network with node set N and link set E . The indices i and j denote a node in the network, $i, j \in N$ and $E \subseteq N \times N$, where $[i, j]$ denotes an undirected link between nodes i and j . Each O-D pair between the base of first responders and the affected population center in the network is represented as a unique commodity type. Let k represent the commodity type index, $k \in K$, where K denotes the set of all commodities. One unit of commodity flow k must be transported over the network from its origin $O(k)$ to its destination $D(k)$. To differentiate the direction of flow of a commodity, we consider two directed links (i, j) and (j, i) corresponding to each original undirected link $[i, j]$. Let A denote the set of the directed links. Each link (i, j) has an associated nonnegative fixed travel time t_{ij}^k which differs for each commodity due to the different operational speeds of different response vehicles. Moreover, all links are capacitated only by their availability status s_{ij} . If the link (i, j) is available then $s_{ij} = 1$, otherwise $s_{ij} = 0$. Parameter b_i^k denotes whether node i is an origin (first responders' base), a destination (affected population center) or intermediate node for commodity k . If node i is an origin for commodity k then $b_i^k = -1$. If node i is

a destination for commodity k then $b_i^k = 1$. If node i is an intermediate node for commodity k then $b_i^k = 0$.

4.3.3 Decision variables

The formulation contains a single set of variables, the arc flow variables denoted by the vector $x = \{x_{ij}^k\}$, which define the flow of different commodities in each of the selected links. If there is a unit flow of commodity k on link (i, j) then $x_{ij}^k = 1$, otherwise $x_{ij}^k = 0$.

4.3.4 The dynamic rerouting formulation

The dynamic rerouting formulation has a single objective, the minimization of the total travel time of all first responders' routes.

The integer programming formulation for the dynamic rerouting formulation is expressed as follows:

$$\text{Minimize: } \sum_{k \in K} \sum_{(i,j) \in E} t_{ij}^k \cdot x_{ij}^k \quad (4.1)$$

Subject to:

$$\sum_{(i,j) \in A} x_{ij}^k - \sum_{(j,l) \in A} x_{jl}^k = b_i^k \quad \forall i \in N, \forall k \in K \quad (4.2)$$

$$x_{ji}^k \leq s_{ij} \quad \forall k \in K, \forall (i, j) \in A \quad (4.3)$$

$$x_{ji}^k \in \{0, 1\} \quad \forall k \in K, \forall (i, j) \in A \quad (4.4)$$

Constraint (4.2) is the conservation of flow for all commodities and nodes. Constraint (4.3) is the capacity constraint for the case that a link is not available (has failed due to the seismic activity). Finally, constraint (4.4) is the integrality constraint of the routing variables.

This formulation is classified as a multi-commodity uncapacitated shortest path problem. It is uncapacitated because the capacity constraint (4.3) does not refer to the summation of all commodity flow variables for a given link.

4.4 Solution methodology

The formulation of Section 4.3 has been classified as a multi-commodity uncapacitated shortest path problem. This formulation does not contain a bounding constraint among the flow variables of the different commodities. Therefore, it can be decomposed to multiple independent instances of the shortest path problem, one instance for each commodity flow. Furthermore, since the shortest path formulation has a totally unimodular constraint matrix, the integrality constraint (4.4) can be linearly relaxed.

The formulation for each commodity k (response route) is:

$$\text{Minimize: } \sum_{(i,j) \in E} t_{ij}^k \cdot x_{ij}^k \quad (4.5)$$

Subject to:

$$\sum_{(i,j) \in A} x_{ij}^k - \sum_{(j,i) \in A} x_{ji}^k = b_i^k \quad \forall i \in N \quad (4.6)$$

$$x_{ji}^k \leq s_{ij} \quad \forall (i,j) \in A \quad (4.7)$$

$$x_{ji}^k \geq 0 \quad \forall (i, j) \in A \quad (4.8)$$

The objective is the minimization of the total time for each individual route. Constraint (4.5) is the conservation of flow for nodes. Constraint (4.3) is the capacity constraint for the case that a link is not available (has failed due to the seismic activity). Finally, constraint (4.4) is the non-negativity constraint of the linear routing variables.

This formulation is solved separately for each commodity k by applying a shortest path algorithm (Ahuja et al, 1993).

4.5 Discussion

This chapter describes the methodological framework for defining the optimal dynamic routes after an earthquake. It consists of 6 methodological components: 1) the static database for storing the network topology, 2) the dynamic database for storing and updating the network status, 3) the optimization component responsible for calculating and proposing the dynamic routes, 4) the verification of the availability status of the proposed routes, 5) the updating of the dynamic network status database in case that certain links in the proposed routes have not been verified, and 6) the final verified dynamic routes. In brief, given the network status, the process iterates until the availability status of all links in the proposed routes have been verified. The corresponding formulation is reduced to multiple shortest paths; one shortest path computation for each first responder's route. The GAMS/CPLEX optimization software

is used to calculate the dynamic routes, for which internet resources, code and the user manual is provided in Appendices G, H and I.

Figure 4.1. Operational flow chart for the calculation of the optimal dynamic routes.

CHAPTER 5. CONCLUSIONS

This chapter summarizes the research, highlights its contributions, and proposes directions for future research.

5.1 *Summary*

This study addressed two objectives. The first objective had a planning perspective while the second objective had an operational perspective.

The first objective was to compare the performance of the IMN with the performance of the CRN of the seismic prone Vincennes district in southwest region of Indiana. This objectives identifies which bridges should be retrofitted before an earthquake, given a limited budget, so that connectivity and population coverage is ensured in the surviving road network after the earthquake.

The following conclusions are summarized from the comparison of the IMN and the CRN (Section 3.3) : (i) the CRN performs better for emergency response operations, where response time is the critical objective, (ii) the CRN provides a wider range of first responders routing and population coverage options, (iii) the cost of retrofitting links belonging to the IMN is a significant percentage of the total budget allocated for the CRN (Figure 3.5), and (iv) the IMN has the high capacity infrastructure that have high daily

volumes; so this infrastructure is important for resuming normal traffic operations after an earthquake.

The second objective was to determine a methodological framework to dynamically reroute first responders when part of a route is unavailable after the earthquake. This objective provides back-up operational response actions when specific road segments of the recommended primary route network fail during an actual earthquake.

The methodological framework is illustrated in the flow chart of Figure 4.1, and summarized hereafter. Before an earthquake, the network topology static database is maintained up to date, thus realistically representing the current network. The network status dynamic database is updated by specifying the current availability status of all links and setting all links to be in unverified status.

Following an earthquake, the optimization component calculates the optimal routes considering the pre-earthquake network status. Then the component responsible for verifying the availability status of the links used in the proposed routes will identify which links in the proposed routes have not been verified. In the case that unverified links do exist, these links are made known to the controller. The controller is responsible for verifying the actual availability status of these links and then update the network status dynamic database accordingly. After the dynamic database is updated, the new optimal routes are calculated. The links in the proposed routes whose availability status has not been verified will have to be verified again by the controller. This process iterates till the

availability status of all links in the proposed routes have been verified, and the optimal verified routes are made available.

5.2 Contributions of the research

In this study an improved formulation for the MCMCNDP was built and a methodological framework and software was developed for the dynamic rerouting of first responders.

The contributions of the research are: (i) the formulation of a mathematical program capable of eliminating all sub-tours in a single computational step (Section 2.4), (ii) the linear relaxation of the binary variables defining coverage and the decision of retrofitting a link (Section 2.4), reducing the computational complexity of the formulation (from integer to mixed integer), (iii) the development of a methodological framework and software for the dynamic rerouting of first responders (Section 4.1), and (iv) the classification of the dynamic rerouting problem as a multi commodity uncapacitated shortest path problem (Section 4.4) which decomposes to multiple independent shortest path problems.

5.3 Future research directions

The research addressed the problem of pre-event planning and post-event operations for the event of an earthquake. It is proposed that the research is integrated into a single decision support system (DSS) which is user-friendly for both planning and operational response. This will aid the actual training of the emergency response agencies. Training is an essential component of emergency response operations. A

complete DSS will familiarize the emergency response agencies with the operations following an earthquake and minimize the response times.

Finally, from a holistic perspective, the long-term survival of the local economy after an earthquake does not depend merely on the effectiveness of the initial emergency response operations. More importantly, the daily traffic volumes on the links should be factored when making retrofit decisions. This is because while earthquakes are rare, the day-to-day usage of a link is of greater importance to the transportation agency. Hence, while earthquake response planning has a limited set of objectives, the transportation agency should take a holistic perspective to identify the critical links for seismic retrofit. This highlights the importance of the links of the IMN.

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APPENDIX

APPENDIX A: NETWORK DATA

Arc ID	Origin node ID	Destination node ID	Link length (miles)	Speed (miles/hr)	Travel time (min)	Bridge area (sq. feet)	INDOT-Maintained
1	1	2	14.20	55	15.49	12555	No
2	2	3	8.50	50	10.20	4299	No
3	3	4	11.50	50	13.80	19422	No
4	5	4	2.10	45	2.80	29279	No
5	6	1	17.00	55	18.55	179029	Yes
6	6	5	1.75	45	2.33	0	No
7	7	5	4.00	45	5.33	61507	No
8	8	6	3.10	45	4.13	139483	Yes
9	8	7	1.50	45	2.00	7535	Yes
10	8	9	2.40	45	3.20	15554	Yes
11	9	10	5.70	65	5.26	104892	Yes
12	11	10	1.54	65	1.42	26414	Yes
13	8	11	5.00	45	6.67	55407	No
14	11	12	1.72	65	1.59	43672	Yes
15	12	7	4.00	45	5.33	0	Yes
16	7	13	3.60	45	4.80	33124	Yes
17	13	14	8.20	55	8.95	8059	Yes
18	12	14	9.90	65	9.14	190749	Yes
19	11	15	3.40	55	3.71	0	No
20	10	16	4.30	45	5.73	0	Yes
21	15	16	3.20	45	4.27	0	No
22	16	17	2.90	55	3.16	11315	Yes
23	17	18	9.60	55	10.47	21530	No
24	15	18	8.90	50	10.68	1087	No
25	12	18	11.40	55	12.44	10223	Yes
26	18	19	5.20	50	6.24	5673	Yes
27	19	20	10.50	50	12.60	27842	No
28	17	20	8.90	55	9.71	66339	Yes
29	19	21	5.20	50	6.24	9998	Yes
30	20	22	3.30	55	3.60	0	Yes

31	22	23	3.00	55	3.27	0	Yes
32	23	24	5.10	50	6.12	1134	No
33	22	24	3.40	55	3.71	3512	Yes
34	24	25	1.20	55	1.31	2288	Yes
35	25	26	6.80	55	7.42	0	Yes
36	26	27	4.70	55	5.13	14055	Yes
37	21	27	3.80	50	4.56	11421	Yes
38	25	28	4.90	45	6.53	9254	No
39	29	28	3.90	50	4.68	4141	No
40	26	29	3.80	50	4.56	5474	No
41	29	30	3.30	50	3.96	3840	No
42	28	31	7.70	55	8.40	10520	No
43	30	31	2.60	50	3.12	0	No
44	31	32	3.30	55	3.60	21273	No
45	27	33	3.80	55	4.15	5048	Yes
46	33	34	4.60	55	5.02	9820	Yes
47	35	34	5.60	50	6.72	1445	No
48	33	35	6.20	50	7.44	8182	No
49	35	30	8.90	50	10.68	14859	No
50	36	34	6.20	50	7.44	4136	No
51	35	36	5.40	50	6.48	2852	No
52	37	36	4.10	50	4.92	0	No
53	32	37	13.80	50	16.56	18809	No
54	38	37	8.70	50	10.44	22758	No
55	39	38	6.00	50	7.20	36508	Yes
56	40	39	19.10	55	20.84	0	No
57	40	38	17.00	50	20.40	30678	Yes
58	41	40	3.40	55	3.71	0	Yes
59	42	41	4.20	50	5.04	0	No
60	42	43	3.40	45	4.53	1968	Yes
61	43	41	2.10	45	2.80	0	Yes
62	32	43	3.40	55	3.71	1440	No
63	44	42	2.30	55	2.51	0	No
64	45	44	29.00	55	31.64	0	No
65	23	45	5.30	55	5.78	50352	Yes
66	46	45	28.00	55	30.55	0	No
67	9	46	10.00	55	10.91	332268	Yes
68	46	47	9.30	50	11.16	0	No
69	47	48	7.90	50	9.48	0	No
70	48	49	8.70	50	10.44	0	No
71	49	1	1.50	45	2.00	35411	Yes
72	2	50	7.00	50	8.40	0	No

73	50	51	6.00	50	7.20	0	No
74	52	51	4.00	65	3.69	65623	Yes
75	2	52	5.20	50	6.24	0	No
76	53	52	8.00	65	7.38	188478	Yes
77	2	54	7.50	50	9.00	55997	No
78	3	54	3.90	50	4.68	2230	No
79	54	55	1.70	50	2.04	2200	No
80	55	53	1.80	65	1.66	22618	Yes
81	55	56	3.00	50	3.60	0	No
82	55	57	4.00	65	3.69	32003	Yes
83	4	57	11.70	50	14.04	960	No
84	57	56	2.50	50	3.00	15712	No
85	57	58	7.30	65	6.74	29832	Yes
86	13	58	8.40	55	9.16	21264	Yes
87	56	59	9.40	50	11.28	2227	No
88	58	59	2.00	55	2.18	1600	Yes
89	58	60	4.50	65	4.15	37137	Yes
90	14	60	2.45	65	2.26	30611	Yes
91	59	61	5.00	50	6.00	8000	No
92	60	61	1.75	55	1.91	0	Yes
93	61	62	8.70	50	10.44	31889	No
94	60	62	10.00	65	9.23	57082	Yes
95	18	62	10.50	55	11.45	18004	No
96	62	63	6.70	50	8.04	6681	No
97	62	64	11.20	65	10.34	31644	Yes
98	63	64	4.60	50	5.52	0	No
99	21	64	11.40	50	13.68	19753	No
100	64	65	2.90	65	2.68	16150	Yes
101	66	64	2.77	50	3.32	11685	No
102	66	65	0.70	50	0.84	0	No
103	34	66	3.50	50	4.20	4292	No
104	34	67	1.90	55	2.07	10763	Yes
105	65	67	3.00	65	2.77	6800	Yes
106	68	67	6.20	65	5.72	35190	Yes
107	36	68	2.40	50	2.88	0	No
108	38	68	10.00	65	9.23	70736	Yes
109	38	70	8.00	50	9.60	16641	No
110	70	69	4.30	50	5.16	0	No
111	70	71	10.50	50	12.60	3923	No
112	68	71	6.80	50	8.16	26085	No
113	71	72	4.70	50	5.64	15814	No
114	67	72	7.40	55	8.07	0	Yes

115	73	72	4.40	55	4.80	1030	No
116	65	73	7.00	50	8.40	10246	No
117	73	74	5.50	55	6.00	6749	No
118	74	75	6.50	55	7.09	0	No
119	62	75	12.20	45	16.27	9193	No
120	75	76	7.00	55	7.64	15769	No
121	77	76	5.50	50	6.60	0	Yes
122	61	77	5.50	55	6.00	20523	Yes
123	78	77	9.50	50	11.40	12451	No
124	59	78	4.20	55	4.58	13496	Yes
125	78	79	7.80	50	9.36	16108	No
126	56	79	6.30	50	7.56	960	No
127	53	79	12.30	50	14.76	16119	No
128	51	80	3.00	50	3.60	0	No
129	80	81	16.00	50	19.20	0	No
130	81	82	4.70	55	5.13	13862	Yes
131	79	82	6.00	50	7.20	7413	No
132	82	83	4.80	55	5.24	7064	Yes
133	78	83	7.80	55	8.51	20561	Yes
134	83	84	1.70	45	2.27	19864	Yes
135	76	84	11.60	55	12.65	5659	No
136	83	85	8.80	55	9.60	36719	Yes
137	85	86	12.30	50	14.76	12647	No
138	84	86	15.00	50	18.00	30708	No
139	86	87	6.50	50	7.80	1515	No
140	76	87	13.40	55	14.62	31599	Yes
141	75	88	7.80	50	9.36	21131	No
142	88	87	4.50	50	5.40	4497	No
143	87	89	10.00	50	12.00	2705	No
144	88	90	8.30	50	9.96	9020	No
145	90	89	2.20	50	2.64	0	No
146	74	90	11.00	50	13.20	33265	No
147	90	91	9.50	50	11.40	4796	No
148	72	91	7.00	55	7.64	17776	Yes
149	71	91	7.60	45	10.13	49043	No
150	91	92	12.10	50	14.52	9165	No
151	92	93	7.10	50	8.52	17262	No
152	69	93	2.60	50	3.12	0	Yes
153	93	94	13.70	55	14.95	49347	Yes
154	92	95	11.10	50	13.32	18344	No
155	95	94	12.50	55	13.64	17136	No
156	95	96	5.90	55	6.44	5097	No

157	91	96	7.30	55	7.96	1646	Yes
158	94	97	1.90	50	2.28	12906	Yes
159	97	98	10.90	55	11.89	26689	No
160	98	99	2.40	55	2.62	8463	No
161	99	100	1.50	55	1.64	29842	No
162	98	101	9.90	50	11.88	21672	No
163	100	101	6.10	55	6.65	22382	Yes
164	96	101	13.80	55	15.05	38426	Yes
165	101	102	14.10	55	15.38	11239	Yes
166	89	102	14.60	50	17.52	26109	No
167	87	102	13.30	55	14.51	51054	Yes
168	103	102	7.30	55	7.96	148031	Yes
169	87	104	10.70	50	12.84	104287	No
170	104	103	4.10	50	4.92	2436	No
171	85	105	4.00	55	4.36	156260	Yes
172	105	104	13.60	50	16.32	3654	No
173	105	106	9.00	55	9.82	21505	Yes
174	106	107	2.80	55	3.05	87265	Yes
175	107	104	8.70	50	10.44	11476	No
176	107	103	11.10	55	12.11	39197	Yes
177	106	108	5.30	50	6.36	0	No
178	107	108	4.50	55	4.91	171805	Yes
179	81	109	24.00	50	28.80	0	No
180	108	109	7.00	65	6.46	0	Yes
181	107	110	3.20	55	3.49	82840	Yes
182	110	111	6.40	55	6.98	31875	Yes
183	110	112	5.00	55	5.45	17728	No
184	112	111	4.30	50	5.16	6781	No
185	103	112	9.20	50	11.04	5396	No
186	112	113	6.00	55	6.55	1224	No
187	113	114	3.20	55	3.49	6911	No
188	102	115	11.10	50	13.32	18980	Yes
189	114	115	6.60	50	7.92	18396	No
190	113	116	6.10	50	7.32	1636	No
191	116	117	5.30	50	6.36	1495	No
192	114	117	5.00	55	5.45	4904	No
193	117	118	2.50	55	2.73	6471	No
194	117	119	3.30	55	3.60	9147	No
195	118	119	1.60	50	1.92	0	No
196	118	120	5.30	50	6.36	41509	No
197	115	121	3.60	50	4.32	7905	Yes
198	121	120	2.60	50	3.12	0	Yes

199	121	122	1.90	50	2.28	0	No
200	122	120	1.90	50	2.28	0	No
201	122	123	9.00	50	10.80	1193	No
202	101	123	12.20	55	13.31	3069	Yes
203	123	124	4.80	55	5.24	5934	Yes
204	125	124	9.00	50	10.80	1400	No
205	126	125	7.40	50	8.88	15616	No
206	127	126	5.20	50	6.24	7993	No
207	128	127	3.95	55	4.31	29665	Yes
208	100	128	25.80	50	30.96	73101	Yes
209	129	128	4.00	55	4.36	127895	Yes
210	99	129	21.00	55	22.91	7935	No
211	126	130	8.70	50	10.44	14612	No
212	125	130	7.90	50	9.48	0	No
213	130	131	1.80	50	2.16	0	No
214	130	132	1.60	50	1.92	0	No
215	132	131	1.20	50	1.44	0	Yes
216	132	133	11.70	50	14.04	20218	Yes
217	124	133	7.90	55	8.62	23066	Yes
218	133	134	4.00	55	4.36	73126	Yes
219	120	134	13.30	50	15.96	55858	Yes
220	134	135	2.50	55	2.73	0	Yes
221	119	135	12.20	55	13.31	10336	No
222	135	136	6.00	45	8.00	7150	Yes
223	119	136	10.20	50	12.24	4652	No
224	136	137	3.00	45	4.00	0	Yes
225	137	138	12.20	55	13.31	23563	Yes
226	116	139	9.60	50	11.52	4594	No
227	111	139	11.70	55	12.76	16390	Yes
228	139	138	7.70	55	8.40	38090	Yes
229	138	140	2.30	55	2.51	7735	Yes
230	140	141	7.90	55	8.62	6214	Yes
231	139	141	17.90	50	21.48	17725	No
232	109	142	19.00	50	22.80	0	No
233	108	142	30.00	50	36.00	0	No
234	142	143	6.20	50	7.44	0	No
235	143	141	5.70	50	6.84	46022	Yes
236	141	144	6.30	50	7.56	5436	No
237	140	145	6.10	55	6.65	3270	Yes
238	144	145	7.00	50	8.40	10580	No
239	145	146	8.90	50	10.68	26237	No
240	146	147	3.70	50	4.44	0	No

241	137	147	6.90	55	7.53	0	No
242	147	148	10.50	50	12.60	3829	No
243	148	149	3.00	50	3.60	2545	No
244	135	150	4.00	55	4.36	2629	No
245	134	150	3.10	55	3.38	7161	Yes
246	150	149	3.10	55	3.38	4315	Yes
247	133	149	9.40	50	11.28	40281	No
248	127	151	17.60	55	19.20	17005	Yes
249	131	151	11.50	50	13.80	0	Yes
250	132	152	11.50	50	13.80	11964	No
251	151	152	6.60	50	7.92	0	No
252	151	153	3.10	55	3.38	0	No
253	153	154	14.10	55	15.38	0	No
254	152	154	11.70	50	14.04	0	No
255	154	155	1.20	55	1.31	0	No
256	149	155	17.80	55	19.42	41432	Yes
257	155	156	6.40	55	6.98	0	No
258	156	157	14.90	50	17.88	0	No
259	148	157	13.70	50	16.44	0	No
260	147	157	12.20	55	13.31	0	No
261	157	158	8.20	50	9.84	0	No
262	146	158	5.10	50	6.12	0	No
263	158	159	8.90	50	10.68	0	No
264	145	159	6.30	55	6.87	0	Yes
265	144	160	5.70	50	6.84	0	No
266	159	160	5.80	50	6.96	0	No
267	143	161	21.80	50	26.16	0	No
268	161	162	2.00	50	2.40	0	No
269	162	163	13.00	50	15.60	0	No
270	163	164	9.00	55	9.82	0	No
271	164	165	12.00	55	13.09	0	No
272	162	166	6.70	65	6.18	0	Yes
273	161	166	7.00	45	9.33	0	No
274	166	165	4.50	45	6.00	0	No
275	166	167	9.00	65	8.31	0	Yes
276	160	167	13.40	50	16.08	0	No
277	159	167	11.40	55	12.44	0	Yes
278	167	168	2.65	45	3.53	0	Yes
279	165	168	2.00	45	2.67	0	No
280	167	169	4.30	65	3.97	0	Yes
281	168	170	4.50	45	6.00	0	No
282	169	171	2.30	45	3.07	0	No

283	171	170	1.00	45	1.33	0	No
284	171	172	7.80	50	9.36	0	No
285	169	172	7.30	65	6.74	0	Yes
286	173	169	3.40	35	5.83	0	No
287	158	173	11.80	50	14.16	0	No
288	173	174	10.40	50	12.48	0	No
289	157	174	7.30	55	7.96	0	No
290	156	174	14.80	55	16.15	0	No
291	174	175	5.00	55	5.45	0	No
292	172	175	4.25	50	5.10	0	Yes
293	170	176	11.70	45	15.60	0	No
294	175	176	5.10	55	5.56	0	No
295	175	177	16.10	50	19.32	0	No
296	175	178	14.50	65	13.38	0	Yes
297	176	183	14.50	55	15.82	0	No
298	178	183	3.90	50	4.68	0	No
299	177	178	5.40	50	6.48	0	No
300	155	179	5.80	55	6.33	0	Yes
301	179	180	10.70	55	11.67	0	Yes
302	177	180	5.60	50	6.72	0	No
303	180	181	2.40	55	2.62	0	Yes
304	178	181	4.00	65	3.69	0	Yes
305	181	182	3.70	55	4.04	0	Yes
306	183	182	2.60	55	2.84	0	No
307	182	184	4.70	55	5.13	0	Yes
308	97	129	20.00	55	21.82	0	Yes
309	39	69	8.00	55	8.73	0	Yes

APPENDIX B: LINK IDs

APPENDIX C: NODE IDs

APPENDIX D: POPULATION DATA

ID	City / Town	Link 1	Link 2	Link 3	Link 4	Link 5	Link 6	Additional assignment in INDOT- Maintained Network	Population
1	Cynthiana	81	84	87	126			82	693
2	Griffin	74	75	76					160
3	Mt. Vernon	71	70						7478
4	New Harmony	1	2	72	75	77		74	916
5	Poseyville	77	78	79				80	1187
6	Darmstadt	86							1313
7	Evansville	8	9	10	13				121582
8	Boonville	23	24	25	26	95			6834
9	Chandler	25							3094
10	Elberfeld	94							636
11	Lynnville	93	94	95	96	97	119		781
12	Newburgh	20							3088
13	Tennyson	99						37	290
14	Chrisney	36							544
15	Dale	46	47	50	103	104			1568
16	Genrtyville	45	46	48					262
17	Grandview	38	39	42				35	696
18	Rockport	32	33	34					2160
19	Santa Claus	49						46	2041
20	Tell City	60	61	62					7845
21	Cannelton	59	60	63					1209
22	Troy	44	53	62				61	392
23	Fort Branch	125						124	2320
24	Francisco	135						121	543
25	Haubstadt	87						124	1529
26	Hazleton	137						171	288
27	Mackey	121	122	123					142
28	Oakland	120						140	2588
29	Owensville	125	126	127	131			132	1322

30	Patoka	136							749
31	Princeton	134	135	138					8175
32	Somerville	121							312
33	Petersburg	139	140	142	143	167	169		2570
34	Spurgeon	119						97	227
35	Winslow	141						140	881
36	Birdseye	109	110	111				152	465
37	Ferdinand	112						108	2277
38	Holland	116						105	695
39	Huntingburg	113	114	115	148				5598
40	Jasper	147	148	149	150	157			12100
41	Bicknell	186	187	190				188	3378
42	Bruceville	183	184	185	186			182	469
43	Decker	171	172	173					283
44	Edwardsport	192						197	363
45	Monroe city	169						176	548
46	Oaktown	227							633
47	Sandborn	194	195	221	223			219	451
48	Vincennes	174	175	176	178	181			18701
49	Wheatland	168	170	176	185				504
50	Alfordville	164							112
51	Cannelburg	165							140
52	Elnora	196	198	200	219				721
53	Montgomery	165							368
54	Odon	201						203	1376
55	Plainville	188	189	197					513
56	Washington	165	166	167	168	188			11380
57	Crane	203							203
58	Shoals	160	161	210				208	807
59	Loogootee	162	163	164	165	202			2741
60	French Lick	153	155	158					1941
61	West Baden Springs	158							618
62	Bedford	207	208	209					13768
63	Oolitic	207							1152
64	Bloomington	248	249	251	252				69291
65	Stinesville	253						256	194
66	Ellettsville	253						249	5078
67	Bloomfield	216	217	218	247				2542
68	Jasonville	240						237	2490
69	Linton	222	223	224					5774
70	Lyons	221						219	748

71	Newberry	219							206
72	Switz	220	221	222	244				311
73	Worthington	243	246	247	256				1481
74	Carlisle	226	227	228	231				2660
75	Dugger	225							955
76	Farmersburg	264							1180
77	Hymera	239						264	833
78	Merom	231						235	294
79	Shelburn	237	238	239	264				1268
80	Sullivan	225	228	229					4617
81	Riley	286	287	288				285	160
82	Seelyville	293						285	1182
83	Terra Haute	278	279	281					59614
84	West Terra Haute	271	274	279				278	2330
85	Brazil	293	294	297				296	8188
86	Center Point	295						296	292
87	Clay city	258	259	260	261	289		296	1019
88	Harmony	297						296	589
89	Knightsville	297						296	624
90	Staunton	293						292	550
91	Spencer	255	256	257	300				2508
92	Cloverdale	303							2243
93	Greencastle	307							9880

APPENDIX E: POPULATION CENTER IDs

APPENDIX F: COMPUTATIONAL RESULTS

Network	Time weight	Total travel time (min)	Population weight	Population covered (persons)	Budget (million sq. feet)	Optimality gap
INDOT-Maintain.	0.975	1747.8	0.025	437448	1.67	2%
INDOT-Maintain.	0.983	1707.0	0.018	437311	1.67	2%
INDOT-Maintain.	0.990	1695.3	0.010	437311	1.67	2%
INDOT-Maintain.	0.995	1695.3	0.005	437311	1.67	2%
INDOT-Maintain.	0.999	1695.3	0.001	432503	1.67	2%
INDOT-Maintain.	0.975	1735.3	0.025	447703	2.00	2%
INDOT-Maintain.	0.983	1679.2	0.018	447703	2.00	2%
INDOT-Maintain.	0.990	1590.5	0.010	435479	2.00	2%
INDOT-Maintain.	0.995	1590.5	0.005	435479	2.00	2%
INDOT-Maintain.	0.999	1587.0	0.001	433923	2.00	0%
INDOT-Maintain.	0.975	1719.7	0.025	449031	2.30	2%
INDOT-Maintain.	0.983	1637.7	0.018	449031	2.30	2%
INDOT-Maintain.	0.990	1622.9	0.010	449031	2.30	2%
INDOT-Maintain.	0.995	1622.9	0.005	443995	2.30	0%
INDOT-	0.999	1588.4	0.001	435479	2.30	0%

Maintain.						
INDOT-Maintain.	0.900	1653.5	0.100	452052	2.67	0%
INDOT-Maintain.	0.950	1653.5	0.050	452052	2.67	0%
INDOT-Maintain.	0.975	1653.5	0.025	452052	2.67	0%
INDOT-Maintain.	0.983	1653.5	0.018	452052	2.67	0%
INDOT-Maintain.	0.990	1621.0	0.010	449031	2.67	0%
INDOT-Maintain.	0.995	1621.0	0.005	449031	2.67	0%
INDOT-Maintain.	0.999	1588.4	0.001	435479	2.67	0%
INDOT-Maintain.	0.900	1653.5	0.100	452052	3.00	2%
INDOT-Maintain.	0.950	1653.5	0.050	452052	3.00	0%
INDOT-Maintain.	0.975	1653.5	0.025	452052	3.00	0%
INDOT-Maintain.	0.983	1653.5	0.018	452052	3.00	0%
INDOT-Maintain.	0.990	1621.0	0.010	449031	3.00	0%
INDOT-Maintain.	0.995	1621.0	0.005	449031	3.00	0%
INDOT-Maintain.	0.999	1588.4	0.001	435479	3.00	0%
INDOT-Maintain.	0.900	1653.5	0.100	452052	3.33	2%
INDOT-Maintain.	0.950	1653.5	0.050	452052	3.33	0%
INDOT-Maintain.	0.975	1653.5	0.025	452052	3.33	0%
INDOT-Maintain.	0.983	1653.5	0.018	452052	3.33	0%
INDOT-Maintain.	0.990	1621.0	0.010	449031	3.33	0%
INDOT-Maintain.	0.995	1621.0	0.005	449031	3.33	0%
INDOT-Maintain.	0.999	1588.4	0.001	435479	3.33	0%

Complete	0.999	1662.63	0.001	408422	1.67	NA
Complete	0.990	1685.59	0.010	410802	1.67	NA
Complete	0.950	1686.69	0.050	410802	1.67	NA
Complete	0.900	1715.19	0.100	411855	1.67	NA
Complete	0.999	1391.75	0.001	413091	2.00	NA
Complete	0.990	1466.27	0.010	429665	2.00	NA
Complete	0.950	1646.53	0.050	434609	2.00	NA
Complete	0.900	1755.28	0.100	434461	2.00	NA
Complete	0.999	1346.02	0.001	427829	2.33	NA
Complete	0.990	1398.75	0.010	445473	2.33	NA
Complete	0.950	1584.67	0.050	449826	2.33	NA
Complete	0.900	1778.19	0.100	450736	2.33	NA
Complete	0.999	1337.23	0.001	435301	2.67	NA
Complete	0.990	1425.29	0.010	450589	2.67	NA
Complete	0.950	1599.52	0.050	453614	2.67	NA
Complete	0.900	1695.34	0.100	455026	2.67	NA
Complete	0.999	1328.15	0.001	436562	3.00	NA
Complete	0.990	1411.76	0.010	451015	3.00	NA
Complete	0.950	1592.24	0.050	455519	3.00	NA
Complete	0.900	1689.16	0.100	456991	3.00	NA
Complete	0.999	1323.77	0.001	436682	3.33	NA
Complete	0.990	1407.76	0.010	452018	3.33	NA
Complete	0.950	1516.12	0.050	456048	3.33	NA
Complete	0.900	1614.49	0.100	457661	3.33	NA

APPENDIX G: THE GAMS/CPLEX RESOURCES

Official site : <http://www.gams.com/>

GAMS User Guides: <http://www.gams.com/docs/gams/GAMSUsersGuide.pdf>

<http://www.gams.com/docs/gams/Tutorial.pdf>

CPLEX User Guide : <http://www.gams.com/solvers/cplex.pdf>

APPENDIX H: THE GAMS/CPLEX CODE FOR DYNAMIC REROUTING

\$offlisting

file RunIDfile /RunIDfile.itm/ , AssemblyID /OutAssemblyIDDR.txt/, Paths /OutPathsDR.txt/ , Warnings /OutWarningsDR.txt/ ;

```
Set i "Nodes" /1*184/;
*Undirected arcs are 307, the directed arcs doubled=> 614
Set j "Directed Arcs" /1*618/;
Set k "Undirected Arcs" /1*309/;
set l "Commodities/Routes" /1*33/;
```

Scalars

```
ResponderRouteIndex "Selection of O-D pair that we are solving for",
WarningIndex "Warning Index" /0/,
RunID "Run ID" ;
```

parameters

```
y(k) "If undirected link k is has been retrofitted or not (0 or 1)",
a(i,j) "Node-arc incidence Matrix: Node i is related to arck j",
t(j) "Travel time of link j in minutes" ,
LinkStatus(k) "Link Status: If Undirected link k is usable" ,
LinkVerification(k) "Link Verification: Links that have been verified" ,
be(k) "If Bridge Exists in Undirected link k" ,
Terminal(l,i) "If node i is a Terminal for responder route l: origin (+1) or a destination (-1)",
DU(j,k) "If directed link j belongs to undirected link k" ,
SingleTerminal(i) "Single Terminal",
LocalPath(k) "Undirected route",
NetSelectedLink(k) "If this link is selected in the final network",
RouteVerificationIndexL "If routing for local OD-Pair has been verified" /0/,
RouteFeasibilityIndexL "If routing for local OD-Pair is feasible" /1/;
```

** LinkStatus and LinkVerification have to be initialized before a series of execution.

** LinkStatus(k)=1 and LinkVerification(k)=0

```
$include ArcNodeIncidence.inc
$include TravelTime.inc
$include BridgeExists.inc
$include LinkStatus.inc
$include LinkVerification.inc
$include RunIDfile.itm
$include DirectUndirected.inc
$include Terminal.inc
```

Positive variables

```
x(j) "If the responder use link j";
```

free variables

```
TotalTravelTime "Objective Variable: Total Travel Times" ;
```

equations

```
TimeObjective "Multiple Objectives",
ConservationOffFlow(i) "Conservation of flow for all nodes i (and all responder routes)",
Capacity(j) "Link is assumed to be accesible only if it is not confirmed that the link is not accesible";
```

```

x.up(j)=1;

TimeObjective..
TotalTravelTime =e= sum( j , t(j)*x(j) ) ;

ConservationOfFlow(i)..
sum( j$( a(i,j)<>0 ) , a(i,j)*x(j) ) =e= SingleTerminal(i) ;

Capacity(j)..
x(j) =l= sum( k$(DU(j,k)=1),LinkStatus(k) ) ;

option limrow = 0 ;
option limcol = 0 ;
option solprint = off;

model MCSP      " ... Practically ALL ... " / TimeObjective, ConservationOfFlow , Capacity / ;

MCSP.reslim = 3600000 ;
MCSP.iterlim = 10000000 ;
MCSP.sysout = 0 ;
MCSP.optfile = 1 ;

AssemblyID.ap = 0;
put AssemblyID ;
put "Iteration, ODpair, TotalTravelTime, ModelStatus, CPUTime, Date, Time" / ;
putclose ;

Paths.ap = 0;
put Paths ;
put "Iteration,ODPair,UndirLink" / ;
putclose ;

Warnings.ap = 0;
put Warnings ;
put "*****" /;
put "***      Start of Warning File for Iteration #" RunID:0:0 "      ***" /;
put "*****" //;
putclose;

RunID = RunID + 1 ;

*****

NetSelectedLink(k)=0;

for (ResponderRouteIndex = 1 to card(l) by 1,

    WarningIndex = WarningIndex + 1 ;

    SingleTerminal(i) = sum( l$(ord(l) = ResponderRouteIndex) , Terminal(l,i) ) ;

    solve MCSP using LP minimizing TotalTravelTime;

    RunIDfile.ap = 0;
    put RunIDfile ;
    put "RunID = " RunID:0:0 " ," ;
    putclose ;

    AssemblyID.ap = 1;
    put AssemblyID ;
    put RunID:0:0 " , " ResponderRouteIndex:0:0 " , " TotalTravelTime.l:0:3 " , " MCSP.solvestat:0:0 " , " MCSP.modelstat:0:0 " , "
MCSP.resusd:0:2 " , " system.date " , " system.time / ;
    putclose ;

```



```

*   Check whether a feasible route exists
RouteFeasibilityIndexL=0$(MCSP.modelstat=4)+1$(MCSP.modelstat<>4);

*   If a feasible route does not exist then mention this in the warning file
if(RouteFeasibilityIndexL=0,

    LocalPath(k) = 0;
    NetSelectedLink(k) = max(LocalPath(k),NetSelectedLink(k));

    AssemblyID.ap = 1;
    put AssemblyID ;
    put RunID:0:0 " , " ResponderRouteIndex:0:0 " , " TotalTravelTime.l:0:3 " , " MCSP.modelstat:0:0 " , " MCSP.resusd:0:2 " , "
system.date " , " system.time / ;
    putclose ;

    Warnings.ap = 1;
    put Warnings ;
    put WarningIndex:0:0 ".1 Routing of emergency responders for origin-destination pair # " ResponderRouteIndex:0:0 ;
    put "in the complete south-west Indiana road network is infeasible due to the unavailability of certain links." / ;
    putclose ;

);

*   If a feasible route exists then mention this and include all links in the route.
if(RouteFeasibilityIndexL=1,

    LocalPath(k) = sum(j,DU(j,k)*x.l(j));

    Paths.ap = 1;
    put Paths ;
    loop( k$(LocalPath(k)<>0) , put RunID:0:0 " , " ResponderRouteIndex:0:0 " , " k.tl:0:0 / );
    putclose ;

    NetSelectedLink(k) = max(LocalPath(k),NetSelectedLink(k));

*   Check all links in the route have been verified
RouteVerificationIndexL = prod( k$(LocalPath(k)=1) , LinkVerification(k) ) ;

*   Case that there are unverified links in the proposed shortest route
if( RouteVerificationIndexL=0 ,
    Warnings.ap = 1;
    put Warnings ;
    put WarningIndex:0:0 ".1. The shortest route of emergency responders for origin-destination pair # "
ResponderRouteIndex:0:0 " has not been verified in the " ;
    put "complete south-west Indiana road network." ;
    put / WarningIndex:0:0 ".2. For routing in the complete south-west Indiana road network the status of the following
links have to be verified:" / ;
    loop(k$( NetSelectedLink(k)=1 and LinkVerification(k)=0),
        put " " k.tl:0:0 ;
        if(be(k)=1, put " (At least one bridge exists in this link)" ) ;
        put / ;
    );
);

*   Case that there all links have been verified in the proposed shortest route
if( RouteVerificationIndexL=1 ,
    Warnings.ap = 1;
    put Warnings ;
    put WarningIndex:0:0 ".1. The shortest route of emergency responders for origin-destination pair # "
ResponderRouteIndex:0:0 " has been verified in the " ;
    put "complete south-west Indiana road network." / ;
);

);

);

```

```
Warnings.ap = 1;
put Warnings ;
put / / /
put "*****" / ;
put "***      End of Warning File      ***" / ;
put "*****" / ;
putclose ;
```

APPENDIX I: GAMS/CPLEX MANUAL

The GAMS/CPLEX manual includes four sections. In Section I the installation of the GAMS/CPLEX software is described, along with the installation of the source code and the input files. In Section II, the input files are described and an indicative example is provided. In Section III, GAMS/CPLEX' execution is demonstrated, and finally in Section IV the format of the output files is described and an indicative example is provided.

SECTION I: SETUP

In this section the latest version (1/31/2006) of the optimization software GAMS v22 is installed, the source code, the input and the output files are copied to the hard disk drive, and the GAMS IDE environment is calibrated.

STEP 1 : Insert “Dynamic Rerouting” CD into the CD-ROM Drive.

STEP 2 : Copy the “D:\Dynamic Rerouting” directory with all the files and subdirectories to c:\ . The directory “D:\ Dynamic Rerouting” includes:

- a) The GAMS executable file : “GAMS22-setup.exe”
- b) The GAMS source code file: “DynamicRerouting.gms”
- c) The input files “*.inc”.
- d) The auxiliary file “RunIDfile.itm”.
- e) The GAMS/CLPEX options’ file: “cplex.opt”
- f) The output files “*.txt”.

STEP 3 : Execute “C:\Dynamic Rerouting\GAMS22-setup.exe”.

Screen 1 : Close all other programs and click “next” to proceed with the installation.

Screen 2 : Install to the default ”C:\Program Files\GAMS22.0” directory.

Screen 3 : Accept the default option “Full installation” and click “next” to proceed with the installation.

Screen 4 : Accept the default option “GAMS” and click “next” to proceed with the installation.

Screen 5 : Accept the default option “Create a Desktop Icon” and click “next” to proceed with the installation.

Screen 6 : Click “Install” to finalize the installation. GAMS is now being installed with the options previously selected.

Screen 7 : The following dialog box appears: “Do you want to copy an existing license file?”. The current version of GAMS allows modeling of any instance of the “Dynamic Rerouting” problem and solves only small instances of it. In order to solve large instances the appropriate license file should be acquired from www.gams.com. The installation can continue by selecting “No”. GAMS is now installed with full modeling and debugging capabilities, and the license file to solve small instances of the “Dynamic Rerouting” problem.

Screen 8 : Click “Finish” to complete the installation and launch GAMS IDE. GAMS IDE is now launched.

STEP 4 : In the GAMS IDE environment, go to File\Options and then Options\Execute. Check “Use following additional parameters”. In the following input box insert “idir "C:\Dynamic Rerouting"”, and click OK to save the inserted options.

STEP 5 : In the GAMS IDE environment, go to File\Options and then Options\Solvers. Check all the options associated with CPLEX. All options should now appear checked with an “X” sign instead of the previous “.” sign.

SECTION II: INPUT FILES

In this section the functionality and the structure of the input files are described. All *.inc input files are editable with a text editor like “notepad”. The INDOT administered network is used as the input network and routing is performed among major population centers.

<u>Input file name</u>	<u>Description and example from the test network.</u>
Terminal.inc:	The information indicating the origin and destination node for each first responder route. For instance, record “Terminal("13","91")=1;” indicates that node 91 is the destination of route 31. This file is part of the static database.
ArcNodeIncidence.inc :	The information indicating the topology of the studied network. For instance, record “a("6","5")=1; a("1","5")=-1;” indicates that link 5 originates from node 6 and ends to node 1. This file is part of the static database.
DirectUndirected.inc :	The information indicating the relation between a directed and an undirected link. For instance, record “DU("310","1")=1;” indicates that the directed link 310 comes from the undirected link 1. This file is part of the static database.

BridgeExists.inc:	The information indicating whether a bridge exists in an undirected link. For instance, record “be("18")=1;” indicates that there is a bridge in undirected link 18. This file is part of the static database.
LinkStatus.inc:	The information indicating the availability status of an undirected link. For instance, record “LinkStatus("10")=1;” indicates that undirected link 10 is available. This file is part of the dynamic database.
LinkVerification.inc:	The information indicating whether the availability status of an undirected link has been verified. For instance, record “LinkVerification("10")=0;” indicates that the availability status of undirected link 10 has not been verified. This file is part of the dynamic database.

SECTION III: EXECUTION

In this section the an instance of the “Dynamic Rerouting” problem is solved. It is noted that there is no reason to edit the source code because all the input parameters are inserted through the input files. In order to solve the “Dynamic Rerouting” problem, it is needed to:

1. Insert the problem parameters in the input files, as previously described, with the use of text editor like “notepad”.
2. Load GAMSIDE (with the GAMS/CPLEX license files installed).
3. Go to File\Open and select the source code file “C:\Dynamic Rerouting\DynamicRerouting.gms”.
4. Select File\Run to execute the code.

SECTION IV: OUTPUT FILES

In this section IV the output files of the “Dynamic Rerouting” problem’s solution are described. They are in the form of text file *.txt format. This format is editable from a text editor like “notepad”.

<u>Output file name</u>	<u>Description and example</u>
OutAssemblyIDDR.txt:	<p>Key characteristics of the solved instance of the “Dynamic Rerouting” problem. From left to right, it includes:</p> <ol style="list-style-type: none"> 1. The serial number of the “Dynamic Rerouting” instance solved. It is strictly an increasing natural number, which is used as the unique ID of the instance. 2. The route ID. 3. The total travel time for that route in minutes. 4. Model status, which is 1 if optimality is achieved. 5. The CPU computational time in CPU seconds. 6. The date of execution. 7. The time of execution.
OutWarningsDR.txt:	<p>This file indicates to the controller which routes have undirected links whose availability status have not been verified. These undirected links are listed. Next to the link ID, the existence of a bridge in that link is indicated.</p>

OutPathsDR.txt: This file includes the undirected links used in the optimal dynamic routes. From left to right, it includes:

1. The “Dynamic Rerouting” instance’s serial number. It is a strictly increasing natural number which is used as the unique ID of the specific “Dynamic Rerouting” problem solved.
2. The route ID.
3. The included undirected links.