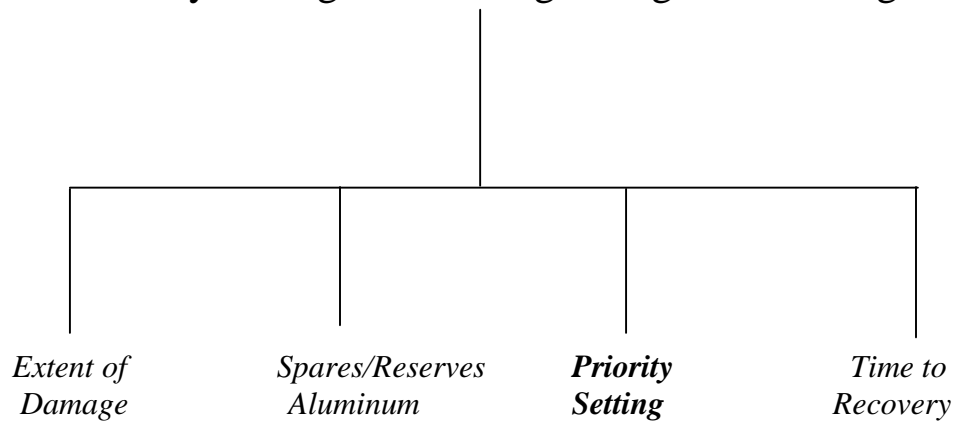


Chapter 4

Critical Replacement of Damaged Equipment

Recovery Management of Signs, Signals, and Lights



4.1 Introduction

The goal of this analysis is to provide a methodology for establishing priorities needed to determine the order of the full recovery of road segments of the Suffolk District. Full recovery refers to the fact that this analysis is being conducted in respect to the re-establishment of permanent traffic control devices as opposed to the temporary replacements installed immediately following a hurricane impact. Once established, the resulting recovery schedule will aid Suffolk District recovery management in making informed decisions concerning the order of traffic control equipment recovery. This recommendation, or priority schedule, will be in the form of a ranking of road segments, where the higher a road segment is on the list, the more important its respective equipment re-establishment is. As mentioned earlier, this equipment will consist of:

- Directional signs (or materials to make such signs)
- Traffic Control Lights on Relevant Collector Roads
- Luminaries along certain highway sections.

Until *all* equipment listed above that was damaged by a hurricane is repaired or replaced, the road segment will be considered in need of recovery. Therefore, when a road segment is re-established or recovered, all equipment that has been damaged by the hurricane is repaired or replaced. In addition, because we can expect significant damage levels from all category hurricanes, this effort assumes that all road segments will experience some damage. Consequently, at the beginning of this analysis, all road segments are ‘down’ or in need of recovery.

The method used to establish the priority schedule is based on the accessibility of critical facilities, however this model allows other statistical data (such as traffic volume) to be the basis for recovery ordering. Section 4.3.1 describes how the number of critical

facilities (hospitals, fire/rescue, and military in this particular case, but not necessarily) associated with each interchange will be used in measuring the importance of recovery of each segment. Therefore the goal of this prioritization is to establish a ranking that enables the quickest and most efficient re-connection of all critical facilities. By “connection,” it is meant that we desire all facilities to have completely re-established routes between each other. A measure of the *connectivity* of the road network is defined to be the number of critical facilities that are mutually accessible, i.e. the number of paths among critical facilities. The number of critical facilities associated with a node will also be referred to as its *weight*.

This measurement technique is made under the assumption that road segments between these critical facilities (listed in section 4.3.1) are the most essential to the well being of the community. Therefore, the importance of a road segment can be quantified as a function of the number of critical facilities to which it provides access. The number of critical facilities will serve as a weight to measure relative road segment importance. Traffic volume through nodes, another possible measurement, for the most part reflects the traffic flows to and from commercial or civic establishments. Our assumption is that fully recovered routes to these establishments are not as valuable to the community as those used to access critical. However, the connectivity algorithm described in section 4.3.2 is designed so a variety of node weighting techniques, such as population statistics, can be used to establish node weight. The scope and assumptions of this project suggested we use the ‘critical facility’ weighting technique described in section 4.3.1. The development and description of the algorithm that will be used to measure the value of segment recovery (as a function of *node weight*) is explained in detail in Section 4.3.2.

4.2 Background

In the days immediately following the impact of a hurricane, the re-establishment of safe and adequate travel conditions is essential to the efficiency of the community's recovery. After the debris from the hurricane has been cleared from the roads, temporary repairs and replacements are made so traffic can begin flowing back into the Suffolk community. However, these temporary fixes are not suitable for the long-term allowance of regular traffic flow. Therefore, when time and resources allow, the recovery process begins re-establishing the permanent signs, signals and luminaries. Because there are limited resources following a hurricane's landfall and most certainly other limiting factors such as manpower, the prioritizing of the repair of damaged roads becomes critical. Once the amount of damage to traffic control devices has been assessed, the recovery operations can begin. This section describes the current situation and any other relevant developments that might be necessary to understanding this project or the approach used therein.

Network analysis has been used in the field of electrical engineering for a long time now, but only in recent decades have the concepts and tools been applied to other applications (Hillier and Lieberman, 1995). Because network models are applicable to such a wide range of situations, many ways of generating descriptive characteristics have been developed and used to assess the attributes of a network. Problems varying from watershed water flow analysis to computer networks have been approached using classic network analysis techniques. However, there is a lack of network analysis tools that consider node weight as a major input for a prioritization. This stems from the fact that there are so many other factors in such a prioritization problem. For example, the weights that have been applied to this network are associated with nodes. But, there are

also characteristics that describe that state of the transportation network, such as traffic volume, that can only be applied to paths of road segments. Variations like this lead to ambiguity in the problem definition. Therefore developing a standard analysis tool that assesses the connectivity of weighted nodes is a difficult task to approach.

According to information obtained at the meeting in Suffolk on November 14th, current VDOT policies for road recovery prioritization are not well developed. The current operations in a state of emergency include judgmental decisions as to the road recovery order. The basis underneath the decisions made by VDOT officials in the past has been the simple prioritization according to Interstate, Primary and Secondary classifications. Any changes beyond this pattern are made by VDOT officials and are based on additional information gathered during the recovery process (VDOT meeting November 1997).

Mr. Steven Decker at the Florida Department of Transportation describes a similar approach to prioritization of recovery. But, FDOT also includes the needs and locations of facilities such as hospitals, nursing homes and shelters in its decision process. In addition, FDOT works closely with local agencies such as Emergency Operation Centers to help coordinate recovery plans and make sure all recovery decisions are based on all information available. FDOT currently places liaisons in most EOC offices during recovery operations, a practice which Decker claims is helpful in the decision making process (Decker Communications, 1997).

The VDOT officials at the Transportation Emergency Operations Center (TEOC) in Richmond contributed some Hurricane Preparedness manuals that contain information valuable to this project. The Hurricane Checklist (VDOT, 1996) is a compendium of information ranging from storm surge measurements to average signal replacement costs.

This information is provided mostly in the form of tables and figures. Some of the highlights of this source are the expected damage to the bridge tunnel facilities, the cost figures for traffic control equipment and maps of the evacuation routes for phase one and phase two evacuations. The identification of these evacuation routes is used later in this paper to help determine which roads should be considered in the network.

4.3 Technical Approach

First the network configuration being considered must be defined. A network is defined by a collection of points or nodes that connected to each other in a variety of ways by a number of segments of paths (Hillier and Leiberman, 1995). Because of the nature of the network being considered for this project, additional nodes will be appended to the model wherever critical interchanges or intersections lie along the roads being considered. Figure 4.1 shows a simplified example of what one of these configurations might look like. The circles represent the nodes of the network. In our model, these will represent interchanges such as the intersection of I-64 and Route 44. The lines connecting these nodes are considered arcs or paths. These could represent the road segments under consideration for recovery. These segments will be identified by the labels of the nodes they connect. For example, segment (5,6), represented in Figure 4.1 with a double line, is the segment that connects node 5 and 6.

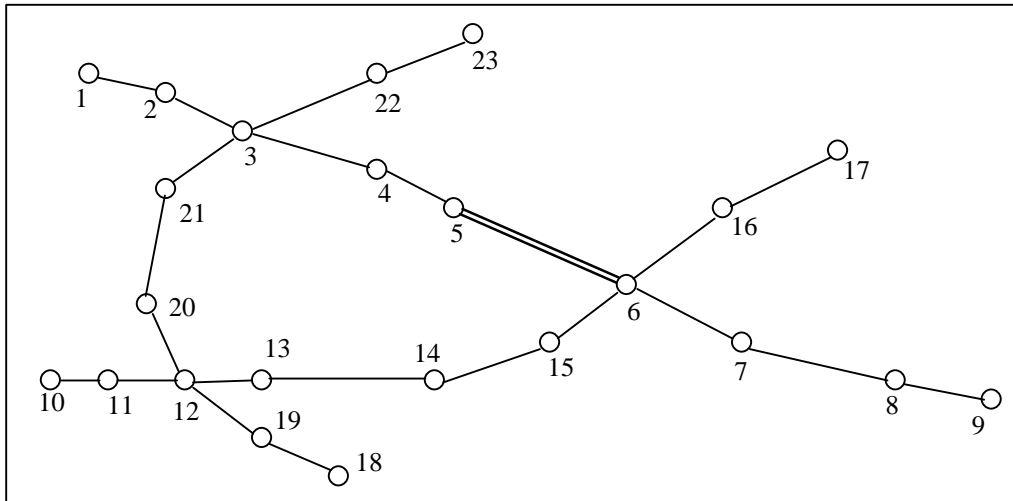


Figure 4.1: Sample network configuration showing exits and interchanges as nodes –
Configuration A

The goal for the recovery process is obviously to achieve the most efficient and most logical road recovery as fast as possible. In this model assumes the logical recovery process can be based on the connectivity of weighted nodes, in our case weighted according to critical facilities. Therefore, “efficiency,” as it applies to this methodology refers to how quickly we can fully re-establish travel routes between all critical facilities. An example of the resulting data can be seen in the graph below. In Figure 4.2, path A would be more attractive than path B because path A achieves higher connectivity in less recoveries than path B. Also, notice the path of the line labeled “Ideal Scenario”. This is the line that would result in the hypothetically ideal situation of all road segments connecting critical facilities being connected immediately. The exact method of connectivity calculation is described shortly. The full connectivity number will be the value associated with all the facilities having fully re-established access to all other facilities.

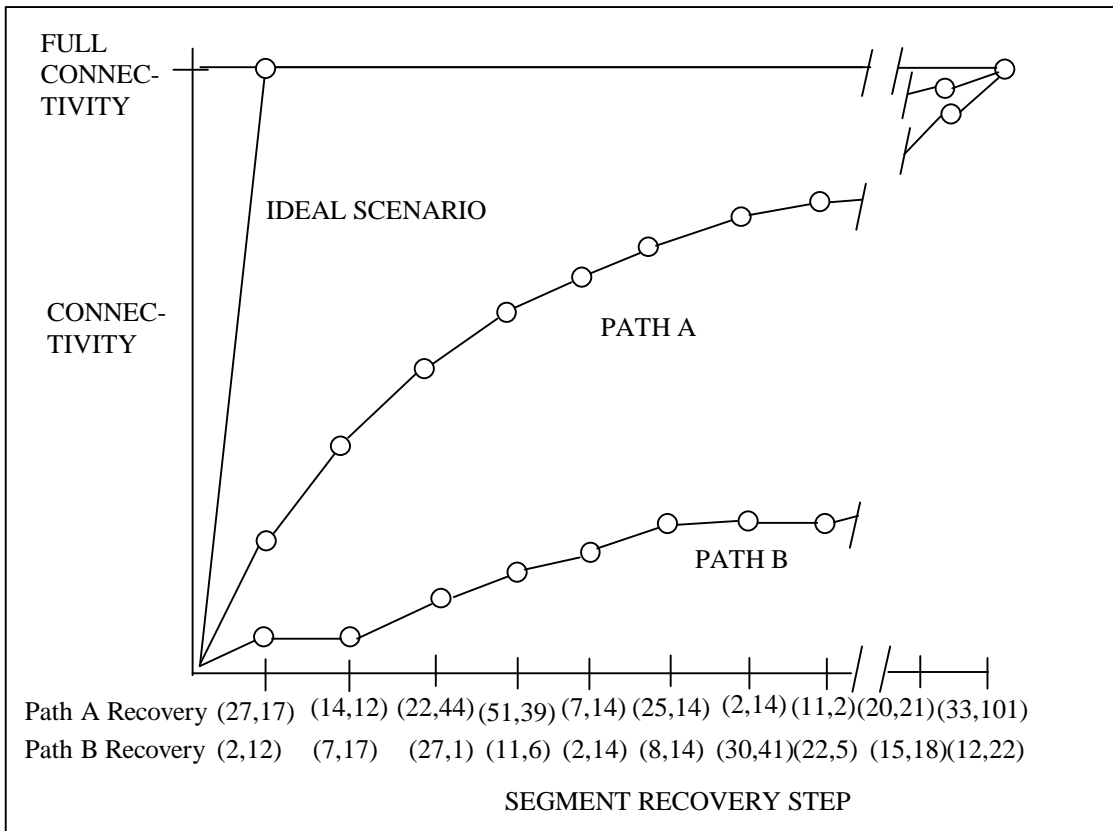


Figure 4.2: Hypothetical connectivity graph, path A being superior.

4.3.1 Network Development

The roads that are being considered to be essential to the Suffolk transportation network are named in the introduction. Determining which roads to be considered was an iterative process. First, a general list of all interstates and other major roads throughout the district were compiled using a map provided by the VTRC (VTRC, 1997) and electronic references provided by Mapquest (Mapquest, 1997). When the initial list was reviewed in a meeting last November with VDOT official in Suffolk, it was recommended that the list of roads be reconsidered (VDOT Meeting Nov. 97). The changes made consisted of the removal of some of the secondary roads that they (the officials) did not consider important to the transportation system because of personal

knowledge. Also, most of the roads listed by VDOT to be the evacuation routes were appended to the list because these have been established as reliable routes in and out of the area even under hurricane conditions (VDOT, 1996). The enlarged map (in Figure 1.1) shows the actual relationship of the interstates and surrounding roads within the Suffolk District. Finally, Figure 4.3 shows a diagram of only the roads being considered in the criticality analysis (as decided in the cooperative effort with VDOT) and their relative location within the Suffolk District. This map is not to distance scale, but the prioritization algorithm discussed in section 4.3.2 is not dependent on distance. The nodes that will be generated by the intersection of the considered roads are shown as black squares. It is important to note that these intersection nodes are not all the nodes that will comprise the analyzed network. The nodes that signify interchanges with roads that lead to critical facilities will be labeled as they are established. Also, any crossing of roads that lacks a black square signifies a crossing without an interchange.

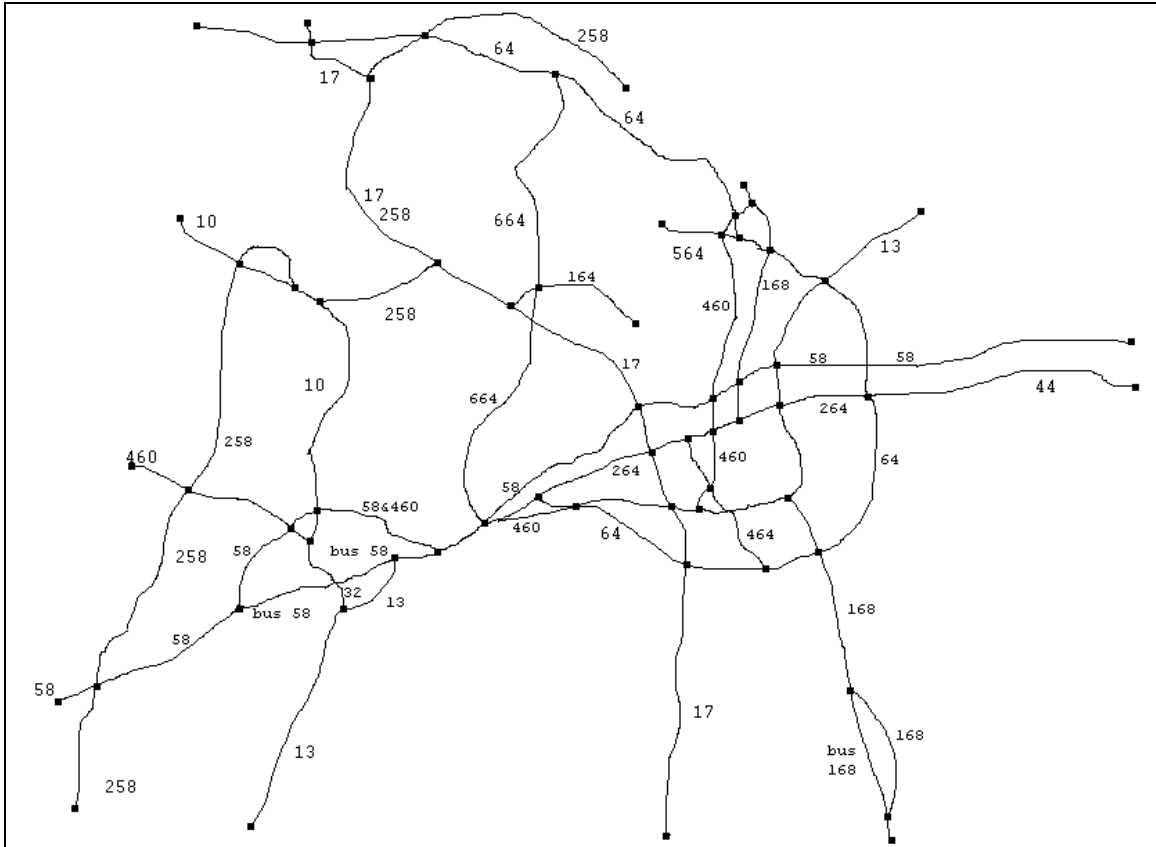


Figure 4.3: The Suffolk District Road Network being considered (not to scale)

Identification of the nodes of the Suffolk transportation network that will serve as nodes in our model began with the marking of all interchanges between the roads being considered by this study. Using the Mapquest (Mapquest, 1997) electronic maps and the map provided by the VTRC, all intersections were labeled and defined as nodes. These nodes are labeled and numbered in Figure 4.4.

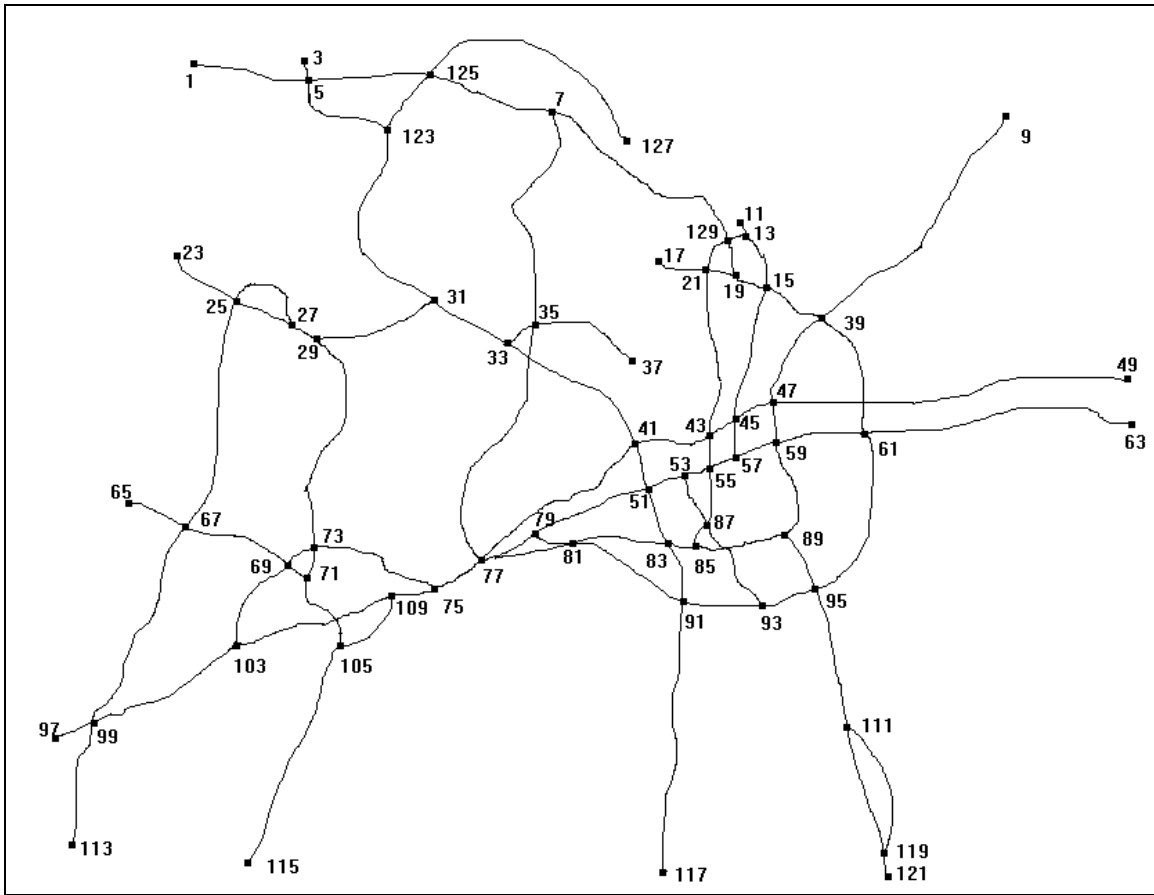


Figure 4.4: The transportation network showing all interchange nodes.

The next step in the node identification process involves finding and labeling all additional facility nodes that are not intersections of two roads being considered, but are used to access the facilities deemed crucial to the communities well-being. These exits, and the number of crucial facilities they provide access to, will be major factors in the calculation of road segment prioritization analysis. An exchange could be considered critical if it is used to access any of the following facilities:

- Military installations
- Power stations
- Communication hubs
- Civil safety facilities (fire, medical, police)

- Hospitals
- Airports

Because of the limited scope of this project, only military installations, hospitals and fire/rescue stations will be considered as critical facilities. Also, all of these facilities will be considered of equal criticality to the community. Although there are obviously more types of facilities that are crucial to a community's welfare, the exact list is dependent on subjective opinion and therefore can vary according who is surveyed. The analysis conducted on military, police, fire/rescue and medical installations will be executed in a way that will be easily replicable if any additional facility types are added in future projects. The implementation of the prioritization algorithm is designed so any node weighting scheme, such as traffic volume or population data, can be used. Therefore it is crucial that the reader remember that any combination of facility types can be used for the formulation described in section 4.3.

The major military installations, fire/rescue stations and medical facilities present in the Suffolk District were identified and then added to Figure 4.4 to make Figure 4.5. Some of the interchange nodes identified in Figure 4.4 were also discovered to provide access to critical facilities. As stated before, a square marker represents an interchange of two roads listed as roads being considered. Underlined numbers represent any of these nodes that are commonly used to access critical facilities. A tabular association of all nodes in the network and their relative weights is listed in Appendix C, table C.1. An excerpt from this table is seen in Table 4.1.

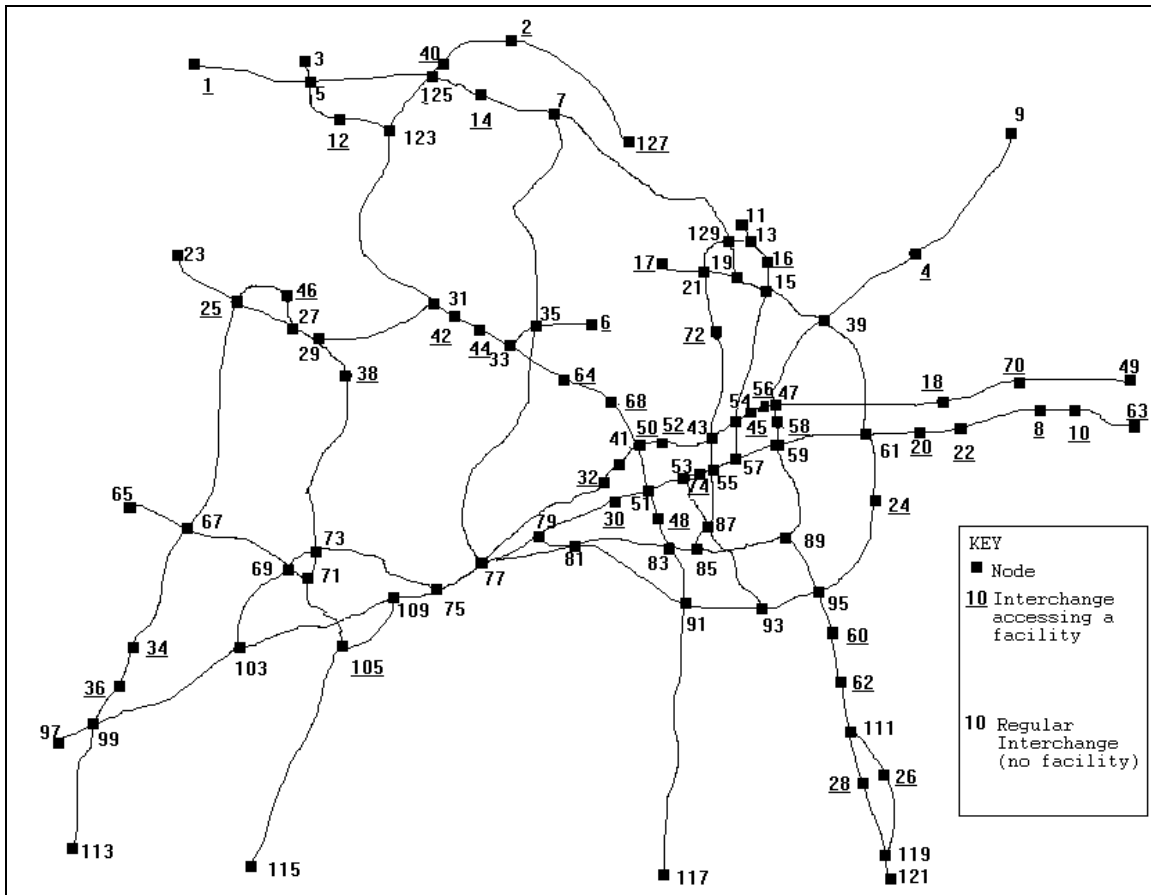


Figure 4.5: All nodes being considered by the criticality analysis

Table 4.1: Sample data from the complete table found in Table C.1

NODE	Road 1	Road 2	Number of facilities (weight)
...
4	13	60	1
5	17	64	0
7	64	664	0

4.3.2 Connectivity Analysis

The main objective of this model is to develop a means for prioritizing the recovery of road segments. This section details the methodology that is used to determine the benefit of segment recovery.

The number of critical facilities accessible by each node was first determined. As stated above, a critical facility is any medical, military, fire/rescue station within the analyzed area. The results of this research are summarized in Appendix D (Table D.1). The number of facilities associated with each node will serve as the weight describing the importance of each node.

The connectivity function that will determine the state of the network after any set of recoveries will be the sum of the number of paths among critical facilities. Let us use a simple example to start. Refer to Figure 4.6.

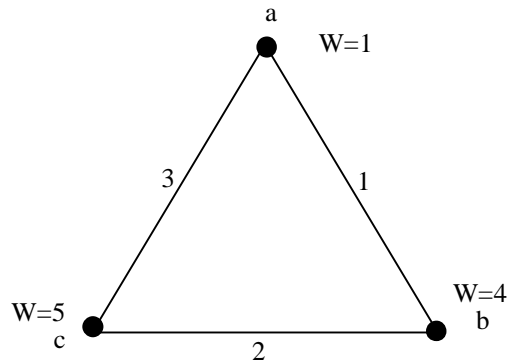


Figure 4.6: Example network with nodes a, b, c and segments 1,2,3.

Consider the network in figure 4.6, each point being a node (labeled a,b,c), and each node connected to both other nodes by a damaged segment (labeled 1,2,3). These nodes ideally represent an interchange between the roads represented by segments one, two and three. Now we assume node weights. Node ‘a’ has one hospital located at it, and therefore has a weight of one. Node ‘b’ has two military bases and two fire/rescue (F/R) stations associated with it, therefore having a weight of four. Node ‘c’ has three hospitals and two F/R stations associated with it, and therefore has a weight of five. If any two of the segments connecting these nodes are recovered (we will use 1 and 2), all three nodes

will have access to each other and we will have achieved full connectivity. Now let's compute the number of facilities that can be reached by any other facility, or the sum of the paths among critical facilities. The facility at node 'a' can access all four facilities at node 'b' by path 1, and all five facilities at node 'c' by taking path 1 and then 2. Therefore our 'accessibility' is now nine (5+4). The four facilities at node 'b' can access the one facility at node 'a' and the five facilities at node 'c' via path 1 and 2, respectively so we add 24 to our accessibility number making it total 33 (9+24). Then, the five facilities at node 'c' can reach the four facilities at node 'b' and the one facility at node 'a'. This adds 25 to our accessibility number, now totaling 58 (33+25). Finally, we must remove the effects of counting any of the connecting paths more than once. In this example there were 13 paths connecting critical facilities that were added unnecessarily. So, subtracting 13 from 58 results in our final accessibility number of 45. Because of the ambiguity of the term 'accessibility', this measurement number will be known as the *connectivity* of the network and will be represented by $C(x)$ where x is the step of the recovery. A recovery step is the complete re-establishment of any road segment. For example, $C(5)$ would be the connectivity of the network after five segments have been recovered.

If the network being considered was more extensive than the one pictured in Figure 4.6 and there are other sub-networks such as this one that contain connected critical facilities, then the connectivity of all such sub-networks will be summed, resulting in the total network connectivity.

There is *inherent connectivity* at any node with more than one facility because each facility has the ability to reach the others, and therefore adds to the total connectivity of the network. This results from the assumption that all facilities residing at the same

node have access to each other. For example, a node with a weight of 10 has ten facilities associated with it. Assuming any one of these facilities can reach any of the other nine facilities, the inherent connectivity for this node is 45. This situation can be imagined as all the facilities in the example above (Figure 4.6) being associated with the same node instead of three different nodes. Therefore, the total inherent connectivity of a network is the sum of the connectivity at each node before any recoveries have been made. The *remaining inherent connectivity* at any recovery step refers to the inherent connectivity associated with all nodes that have not been connected to any other node through the current recovery step. This same number can be calculated as a combination of 10 choose 2 (also referred to as Combo 10,2), meaning between 10 facilities, how many distinct paths connect any two. The equation for a combination function is shown in Equation 4.1.

Equation 4.1: Combination formula

$\mathbf{A \text{ choose } B = Combo A,B = \frac{A!}{B!(A-B)!}}$
--

(! refers to the factorial of the preceding number)

This mathematical method also applies to the total connectivity calculation after iterative recoveries have been made. If this theoretical node of weight nine was connected to another node of weight three, C(1) would equal (Combo 12,2) or (12 choose 2) or 66. In fact, this method of combinatorics is applied to the whole network to calculate total connectivity. The connectivity at any point during recovery is the sum of all combinations available in the network. This function represents the sum of the number of paths among critical facilities.

The maximum connectivity achievable in this network is the combination of all critical facilities in the Suffolk District. This occurs when any facility in the district has fully re-established roads connecting it to all other facilities. There are 64 identified critical facilities in the Suffolk District as I have defined them, therefore the maximum connectivity will be achieved when all 64 facilities have access to each other. The total connectivity at this point in recovery is the combination of 64 choose 2 or $(\text{Combo } 64,2) = 2016$. When recovery procedures meet this connectivity, our goal has been achieved. However it is important to note that this does not necessarily mean all roads in the model network have been re-established. It simply means that all facilities have a fully recovered path to all other facilities.

To achieve a connectivity graph similar to the ideal path in Figure 4.2, the segments that provide the most connectivity must be recovered first. Initially, the sum of all inherent connectivity of the Suffolk road network provides a starting connectivity value of $C(0) = 31$. This is the sum of all the N choose 2 combinations for each node where N is the weight of each node not yet connected to anything. The next step is to find which segment recoveries will result in the largest increase in connectivity. This will be done according to many 'Methods': the one+, two+ and descriptive methods. The one+ step process refers to considering only one segment recovery benefits in the decision of which recovery to conduct next (i.e. one at a time). This is the case until all possible recoveries result in no additional connectivity. At this point, any two steps are considered simultaneously (i.e. two at a time), again comparing the additional connectivity achieved with the recovery of the segment pairs being considered. The details of the two+ and descriptive method are described later in the paper. Ties occurring when all possible re-establishments result in the same increase in connectivity

will be broken arbitrarily. An example of the one+ step process is conducted on the sample network in Figure 4.7 below. The nodes for this example are labeled by letters 'a' through 'j'. The number next to each node gives the weight of each node.

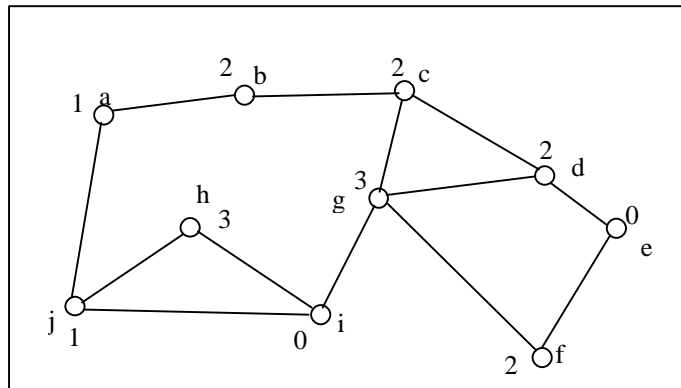


Figure 4.7: Sample network for connectivity problem example

The steps of the methodology would go as follows:

1. The inherent connectivity or $C(0) = 10$, $C(\text{final}) = (\text{sum of all weights}) \text{ choose } 2 = 16$
 $\text{choose } 2 = (\text{combo } 16, 2) = 120$
2. Recover segment (g,c): Connectivity $C(1) = \text{combination of } 5 \text{ choose } 2 (\text{combo } 5,2) +$
 $\text{remaining inherent connectivity}$
 $= 10 + 6 = 16$
3. Recover segment (g,d): Connectivity $C(2) = (\text{combo } 7,2) + \text{remaining inherent } C$
 $= 21 + 5 = 26$
4. Recover segment (g,f): $C(3) = (\text{combo } 9,2) + \text{remaining inherent } C$
 $= 36 + 4 = 40$
5. Recover segment (b,c): $C(4) = (\text{combo } 11,2) + \text{remaining inherent } C$
 $= 55 + 3 = 58$

6. Recover segment (b,a): $C(5) = (\text{combo } 12, 2) + \text{remaining inherent } C$: here there is no inherent connectivity lost because the inherent connectivity of a is 0

$$= 66 + 3 = 69$$

7. Recover segment (a,j): $C(6) = (\text{combo } 13,2) + \text{remaining inherent } C$

$$= 78 + 3 = 81$$

8. Recover segment (j,h): $C(7) = (\text{combo } 16,2) + \text{remaining inherent } C$: here there is no remaining inherent connectivity because all weighted nodes have been connected to other nodes

$$= 120 + 0 = \text{full connectivity} = 120$$

9. Now we have all criticality facilities recovered, but lack two nodes and six paths.

The next step could be done according to many methods, but we will continue our recovery by re-establishing the shortest path with the shortest path (in miles). If this method of breaking ties is unacceptable, one might consider the cost (in \$ or time) of each tied segment and choose the least expensive.

The two+ step method would simply start by comparing the added connectivity of any combination of two segments, instead of one. Using this multiple step forecasting, the effects of zero-weight nodes will be reduced. In the one+ step method, two heavily weighted nodes separated by one node with zero weight will not be considered for connection because a segment re-establishment between either weighted node and the zero weight node will not increase connectivity. Therefore, these two segments (or the two weighted nodes) will not be connected, even if connection would greatly increase the total connectivity. If a two+ step method was used, this zero weight node would be

overlooked, and the two segments connecting the two weighted nodes would be re-established.

Finally, a simulation of a post-hurricane recovery will be executed using the current policies VDOT maintains for this situation. The current policy utilizes the classification of roads into interstate, primary and secondary divisions. It is in this general order VDOT proceeds with recovery of roads. By simulating this order and tracking the connectivity it provides, this effort compares the current policy to those suggested by this criticality analysis.

Another quality associated with this measurement of connectivity is that it is applicable to any network that contains nodes to which weights can be attached. This could be of assistance to VDOT if there is some other method of measuring a node's importance that proves more reliable than the critical facility theory. For example, in the months following a hurricane, the value of a road segment might be a function of the population or the number of homes that the road provides access to. In this model, instead of weighing the nodes by the number of critical facilities they provide access to, one might consider the number of families housed within a certain radius of the node. Or, if traffic volume was the predictor of importance, one might ignore nodes all together and assign weights to the specific road segments instead. The point is, any network, transportation or not, can use the connectivity principal to describe the state of the network.

4.4 Results

The connectivity algorithm was executed upon the model network established in Section 4.3. The results of the recovery prioritization vary according to the method (step-number) used in the algorithm. The execution of the algorithm and the comparison of the increases in connectivity of the network on a step-by-step basis were conducted using Microsoft Excel spreadsheets. These spreadsheets are fully revealed in Appendix C, Tables C.1 and C.2. A section of one of these spreadsheets is pictured in Table 4.2.

Table 4.2: An example of the spreadsheet used to execute connectivity algorithm.

Segments re-established			34,36		25,46		10,63
NODE #	W	Combo(N,2)	W	C	W	C		
1	1	0		1	0		1	0
2	1	0		1	0		1	0
4	1	0		1	0		1	0
6	1	0		1	0		1	0
8	1	0		1	0		1	0
10	1	0		1	0		1	0 V
12	1	0		1	0		1	0
14	3	3		3	3		3	3
16	1	0		1	0		1	0
17	1	0		1	0		1	0
18	3	3		3	3		3	3
20	2	1		2	1		2	1
22	2	1		2	1		2	1
24	3	3		3	3		3	3
25	2	1		2	1 V			
26	1	0		1	0		1	0
28	1	0		1	0		1	0
30	1	0		1	0		1	0
32	1	0		1	0		1	0
34	1	0 V						
36	4	6 X		5	10		5	10
38	1	0		1	0		1	0
40	2	1		2	1		2	1
42	1	0		1	0		1	0
44	1	0		1	0		1	0
45	1	0		1	0		1	0
46	2	1		2	1 X		4	6
48	2	1		2	1		2	1
50	1	0		1	0		1	0
52	3	3		3	3		3	3
56	1	0		1	0		1	0
58	1	0		1	0		1	0
60	1	0		1	0		1	0
62	1	0		1	0		1	0
63	3	3		3	3		3	3 X
64	1	0		1	0		1	0
68	1	0		1	0		1	0
70	1	0		1	0		1	0
72	2	1		2	1		2	1
74	1	0		1	0		1	0
105	3	3		3	3		3	3
127	1	0		1	0		1	0
Total Connectivity		31		35		39		
Steps			1		1		1	
Step #			1		2		3	

The node labels of all the nodes with a weight greater than zero are listed down the left hand side of the table. The total connectivity of the network is kept track of along the bottom of the respective column. Each set of three columns represents one segment re-establishment and is enumerated along the bottom of the respective columns. The set of three columns is made up by one column representing each node (or set of nodes) total weight, one column showing the combination of the node weight (choose 2) and one column showing which two nodes to connect next. The 'V' symbol and the 'X' symbol mark the two nodes, or the segment, being re-established. This selection was made according to which segment re-establishment results in the largest increase in total connectivity, listed at the bottom. As the process continues, individual nodes become part of sets of nodes. When this occurs, the set of nodes is referred to as the largest node number in the set. For example, if nodes 10, 12, 44, and 102 all had access to each other, this set of nodes would be referred to as 102. Therefore, any re-establishments made connecting any other "new" node to this set of nodes is represented on the spreadsheet by a connection of the "new" node to node 102.

The full executions of the one+ and two+ step methods are shown in Appendix C, Tables C.2 and C.3 respectively.

Because of the complexity of the computations, only the one+, two+ and current policy approaches were executed, even though an infinite number of step considerations could be conducted (three, four-step, etc.). Therefore, unless they reveal strictly general info, the following section will be arranged according to the method applied.

4.4.1 One+ Step Method

The one+ step method of algorithm execution considered at first only the nodes that are ONE SEGMENT away from any other nodes. Therefore, the next step at any point in the algorithm was the one segment recovery that increased total connectivity of the network the most. However, after 14 one-step connections, all possibilities for the 15th step resulted in no additional connectivity. At this point, instead of breaking the “0” tie arbitrarily, the two-step method was employed. The two-step method used to determine the next two steps whenever the one-step method provided no additional connectivity. However, if a one-step connection became available, it was automatically taken. This approach of switching between the one-and two-step method was used until there was only one node unconnected. At this point, a three-step (or three-segment) recovery provided the last connection. This mixing of the number of steps used to determine the next move of the algorithm resulted in the naming of this method the one+ step method.

Table 4.3: Sequence of re-establishments resulting from the one+ step method

Step #'s	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Segment 1	34,36	25,46	10,63	20,22	18,70	50,52	8,10	22,8	43,52	64,68	2,40	40,127	42,44	60,62

Step #'s	15,16	17,18	19,20	21,22	23	24,25	26,27	28	29,30	31,32	33,34	35	36,37
Seg1	61,20	24,95	25,67	62,111	111,26	59,58	58,47	47,56	47,39	56,54	45,43	50,68	64,33
Seg2	24,61	95,60	67,34	111,28		61,59	47,18		39,4	54,45	43,72		33,44

Step #'s	38,39	40	41,42	43,44	45,46	47,48	49,50	51,52	53,54	55,56	57,58	59,60	61,62
Seg1	51,48	30,51	50,41	33,35	72,21	39,15	125,40	123,125	42,31	29,38	29,27	5,1	51,53
Seg2	50,51		41,32	35,6	21,17	15,16	125,14	123,12	123,31	31,29	27,46	12,5	53,74

Step #'s	63,64,65
Seg1	38,73
Seg2	73,71
Seg3	71,105

The one+ step method resulted in a recovery schedule that achieves full connectivity in 65 segment re-establishments. There were multiple instances of arbitrary tie breaking, meaning that a fully informed VDOT administrator could use his experience and knowledge to better the recovery process beyond the quality of the connectivity algorithm itself. The resulting sequence of segment re-establishments is listed Table 4.3.

4.4.2 Two+ Step Method

The two+ step method consisted of principals very similar to that of the one+ method. But, instead of the one-segment connection considered at the beginning of the one+ method, the two+ step method goes directly into comparison of what TWO segment recoveries will result in the greatest increase in total connectivity. Here it is important to note the fact that the two steps taken did not have to be in the same direction or area. This means that a pair of one-step recoveries could be made if it resulted in a larger increase in connectivity than any two-step recoveries available. The execution of the two+ method ran smoothly through the networking of all but one node; the same node left at the end of the one+ execution. This node was again connected with a three-step recovery. The execution of the two+ step method also commonly involved the arbitrary breaking of ties. This, again, means that if the algorithm was conducted by VDOT administration, the decision-maker could use his knowledge to better the recovery decisions when these ties were encountered. This method resulted in 66 steps or re-establishments needed to achieve full connectivity. These segment recoveries are listed in order of priority in Table 4.4.

Table 4.4: Sequence of re-establishments resulting from the two+ step method

Step #	1,2	3,4	5,6	7,8	9,10	11,12	13,14	15,16	17,18	19,20	21,22	23,24	25,26	27,28
Seg 1	20,22	8,10	20,61	61,59	58,47	18,70	24,95	60,62	47,39	62,111	111,26	56,45	54,43	43,52
Seg 2	22,8	10,63	61,24	59,58	47,18	47,56	95,60	34,36	39,4	111,28	25,46	45,54	43,72	52,43

Step #	29,30	31,32	33,34	35,36	37,38	39,40	41,42	43,44	45,46	47,48	49,50	51,52	53,54	55,56
Seg 1	52,50	50,51	68,64	39,15	72,21	64,33	33,35	35,7	14,25	40,2	44,42	50,41	43,55	40,123
Seg 2	50,68	51,48	51,30	15,16	21,17	33,44	35,6	7,14	125,40	2,127	42,31	41,32	55,74	123,12

Step #	57,58	59,60	61,62	63,64	65,66,67
Seg 1	12,5	31,29	29,27	25,67	38,73
Seg 2	5,1	29,38	27,46	67,43	73,71
Seg 3	DNE	DNE	DNE	DNE	71,105

4.4.3 The Current Policy Method

As mentioned previously section 4.3, the current policy for segment re-establishment order is based on road classification as interstate, primary, and secondary. The re-establishment basically follows this relative order. This approach to the recovery process was mimicked by this effort to compare the effectiveness of the current policy to the recovery procedures resulting from following the connectivity algorithm. A sequence of recoveries was formulated, concentrating on interstates first, primary roads second and secondary roads last. Because the number of segments in each of these classifications is large, the actual order of recovery can greatly vary. It is for this reason that the sequence of recoveries taken for this method is not listed. However, after the first 66 steps taken the total connectivity was 569 (out of 2016) whereas the other two methods had already reached full connectivity. This fact alone makes the current policy method inferior to the one+ and two+ methods.

4.4.4 The Comparison of Methods

The results from the execution of the three methods described above are summarized by the graph in Figure 4.8. This graph shows the step-by-step connectivity comparison of the first 66 road segment re-establishments for all three methods.

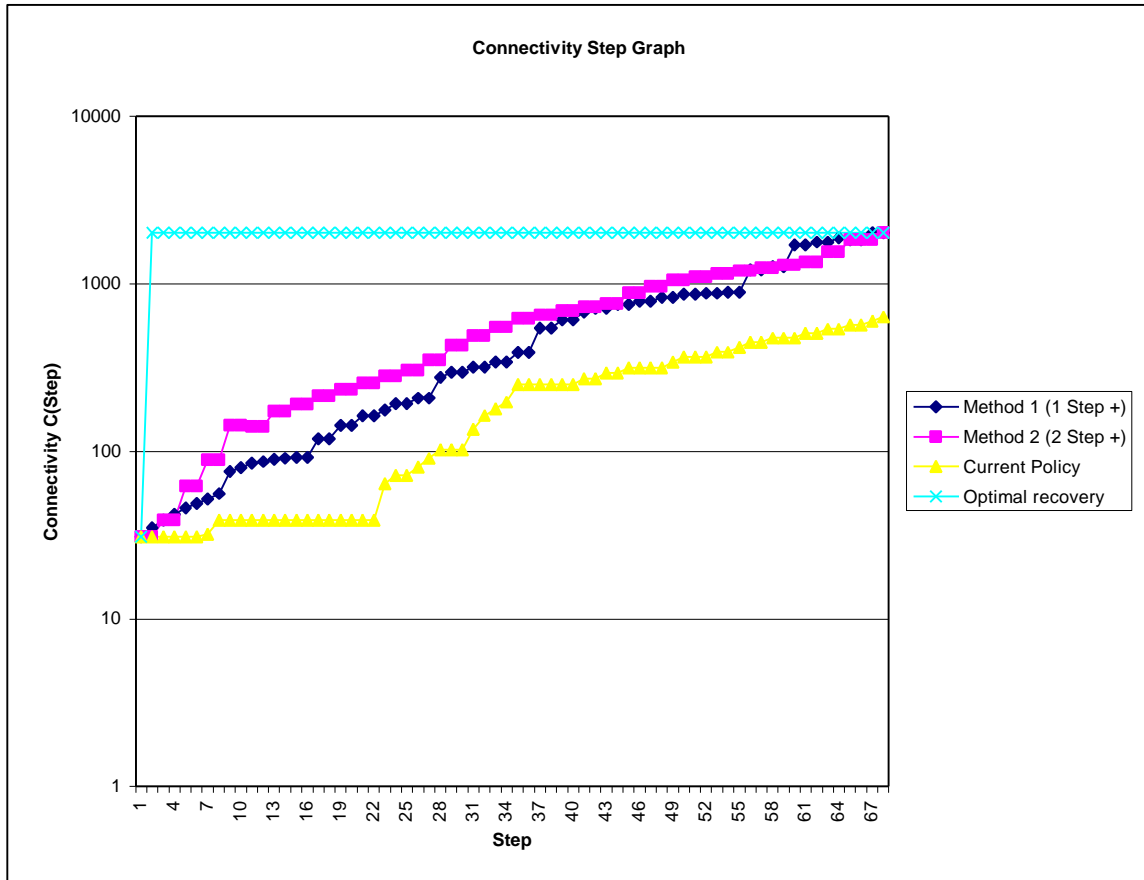


Figure 4.8: Connectivity graph comparing all three methods

4.5 Conclusions and Recommendations

The conclusions derived from the results of the execution of the prioritization algorithm show conclusive evidence supporting the effectiveness of the approach developed for this aspect of hurricane recovery. This section details these conclusions, notes their effectiveness and flaws, and comments on the additional applicability.

Upon inspection of the graph in Figure 4.8, it becomes clear that the two+ step method provides superior connectivity for a great majority of the first 66 segment recoveries. As stated in section 4.3 and shown in Figure 4.2, the goal of the algorithm is to achieve the maximum amount of connectivity as fast as possible or in a minimum number of segment recoveries. Because the two+ step method achieves and maintains more total connectivity than any other method for the majority of the first 66 recovery steps conducted, it will provide the Suffolk District with the most efficient and effective recovery sequence. As seen in Figure 4.8, the one+ step method provides more connectivity than the two+ method for a small number of recoveries, but not enough to challenge the superiority of the two+ step method. Furthermore, a continuing increase in the efficiency of the recovery process can be expected to occur with an increase in the number of segments considered for each recovery step. This conclusion is also derived from the fact that the two+ step method maintains higher connectivity than the one+ step method for the majority of the first 66 segment re-establishments. The further the decision-maker can see into the future (as future applies to segment re-establishment steps), the more informed his decisions will be as to which segment to recover next. This added information makes each decision more effective and more valuable in terms of the connectivity it provides. However, there is a point where the connectivity is achieved at a maximum efficiency, and any change would require a sacrifice at some point during the

process. Therefore, there is definitely an upper limitation to the improvement achieved with multiple step considerations. For example, if there was a choice between more connectivity early with less later in the recovery and the opposite scenario, all else being equal, which is better? When tradeoffs such as this are encountered, the judgement of the decision-maker comes strongly into play.

It can also be concluded that both the one+ and two+ methods are superior to the current VDOT policies. However, one must recognize that the vast majority of the segments that make up the Suffolk District transportation network do not contain intersections (or nodes) that are used to access critical facilities. Therefore, there are significant advances being made toward a fully recovered transportation network, but these advances do not help reach our goal of maximized connectivity of all critical facilities. The effect or achievement attained by recovering these un-weighted segments could be brought to view in the future by assigning a minimal amount of weight to all nodes that have no weight otherwise.

A major limitation of this model is the lack of time and monetary considerations. The length and number of signs required for each road section might play a major role in the decision process conducted by VDOT recovery administration. If this is the case, the weighting mechanism chosen to weight the nodes of the network might reflect the factors of time, money and/or segment length.

Future applications of this approach include, but are by no means limited to the step-by-step estimation of VDOT's replacement equipment needs. If the number and type of all intersections throughout the district could be determined, along with their respective equipment needs, then the equipment needs associated with each individual segment re-establishment could be found. This would in turn help VDOT make more

accurate estimations of the financial and equipment preparation needed to facilitate an efficient recovery.

In conclusion, a weighted measurement technique that assesses the quality associated with each segment recovery can aid VDOT recovery facilitators in the administration of road re-establishment efforts. This in turn can help an unfortunate community affected by a hurricane regain its civic well being through an efficient and effective return to standard traffic conditions. In addition, a recovery prioritization model such as this one can be applied to any community where a major disaster has resulted in the crippling of the transportation network. Thus, this adaptive model can provide support to any traffic engineer's decision making process, improving the effectiveness and efficiency of road re-establishment.