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# Risk-Based Post-Hurricane Recovery of Highway Signs Signals and Lights

prepared by:

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for the

Virginia Department of Transportation

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# Acknowledgements

## Virginia Department of Transportation:

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# Team Visiting in Suffolk District



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# Presentation Outline

- Introduction
  - Mission Statement
  - Project Schedule
  - Data Resources
  - Overview of Technical Approach
- Technical Approach
  - Extent of Damage
  - Aluminum and Spares
  - Priority Setting
  - Time to Recovery
- Conclusions and Recommendations



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# Introduction



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# Mission Statement

To aid the Virginia Department of Transportation (VDOT) in improving the post-hurricane recovery of highway signs, lights, and signals through assessment of the risks, costs, and benefits of alternative plans.



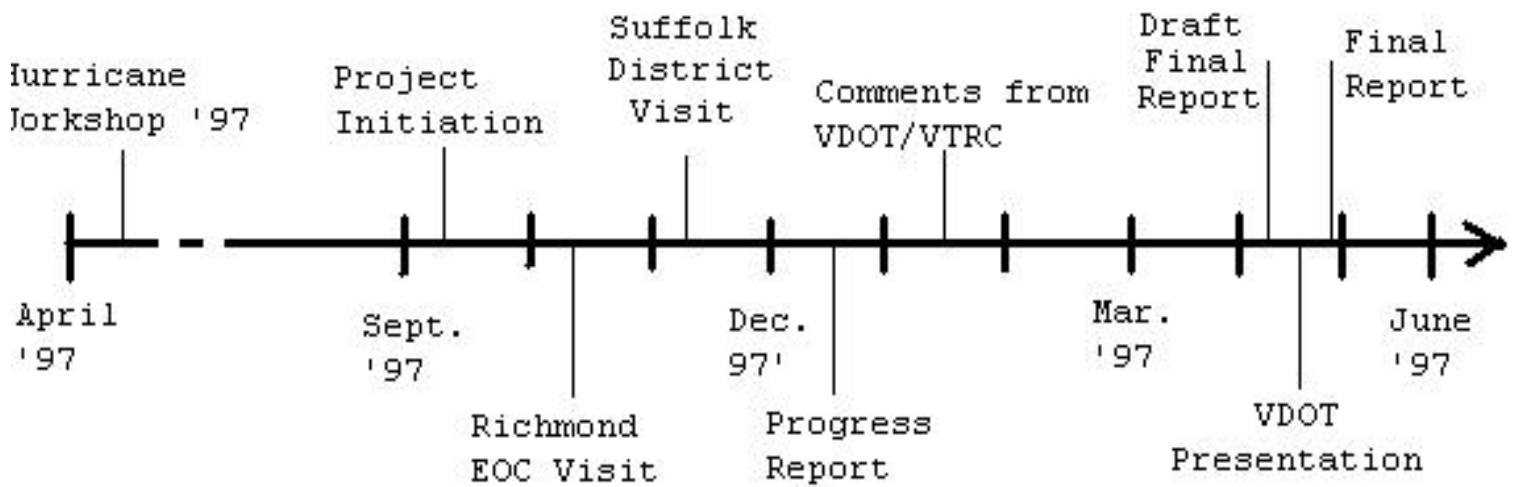
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# Highway Lights and Cantilever Sign



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# Project Schedule



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# Highway Overhead Sign and Lights



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# Data Resources

- Hurricane Damage Assessment for Major Structures in Hampton Roads (VDOT, 1997)
- Commonwealth of Virginia Emergency Operations Plan (VDOT, 1997)
- Transportation E.O.C. Hurricane Checklist
- Standard Operating Procedures for VDOT Tiger Teams (VDOT, 1997)
- Interviews, VTRC Library



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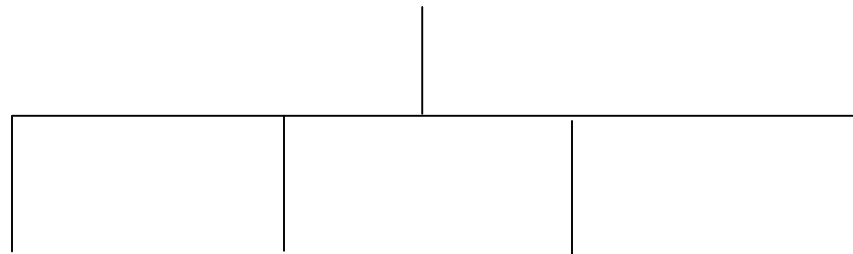
# Highway Light and Sign on Bridge



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# Overview of Approach

## *Recovery Management of Signs, Signals and Lights*



*Extent of  
Damage*

*Spares/Reserves  
Aluminum*

*Priority  
Setting*

*Time to  
Recovery*



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# Map of Suffolk District



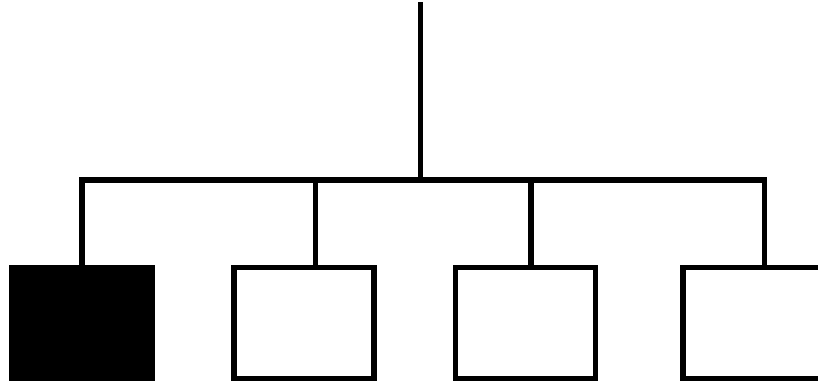
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# Technical Approach



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# Extent of Damage

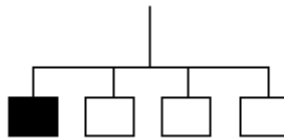


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# Objective

Extent of Damage

The objective of this approach is to develop a model for evaluating sign strengthening alternatives through characterization of hurricane impacts.

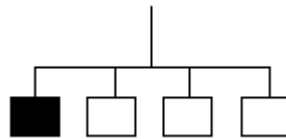


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# Overview of Approach

## Extent of Damage

- Sensitivity analysis of ultimate wind velocities for sign structures
- Characterization of sign damage under uncertainty
- Damage by hurricane category
- Comparison of sign strengthening alternatives



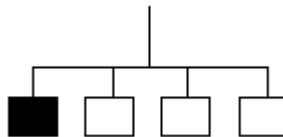
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# Sensitivity Analysis

Extent of Damage

- Expected failure points of sign structures (VDOT, 1997):

| Damageable Equipment       | Ultimate Wind Velocities (mph) |
|----------------------------|--------------------------------|
| Roadside Sign Structures   | 86                             |
| Cantilever Sign Structures | 117                            |
| Overhead Sign Structures   | 121                            |



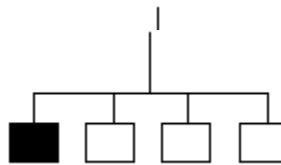
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# Sensitivity Analysis

Extent of Damage

Ultimate Wind Velocity ( $V_u$ ) Formula (VDOT, 1997)

$$V_u = \frac{\sqrt{(1.3 \times V) \times (F_u - F_{bII} \times D_{lr})}}{F_{bII} \times W_{lr} \times 1.3}$$

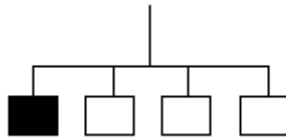


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# Sensitivity Analysis

Extent of Damage

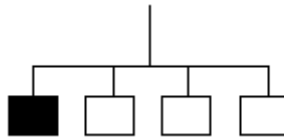
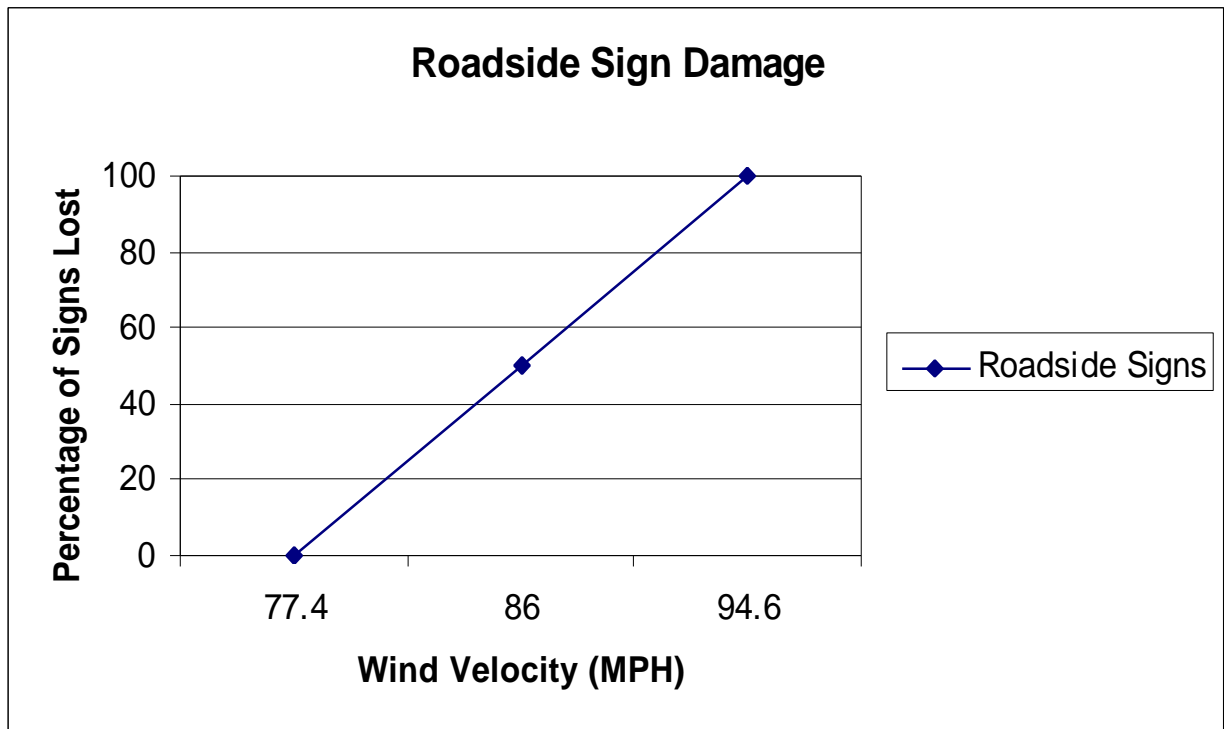
- Ultimate wind velocity equation is sensitive to variation in its components.
- Because the ultimate wind velocity is sensitive, a *range of values* should be used to represent sign damage.



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# Ranges of Wind Velocities

Extent of Damage



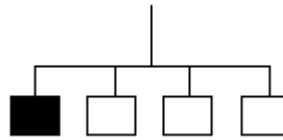
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# Damage by Category

Extent of Damage

Hurricane wind speed by category:

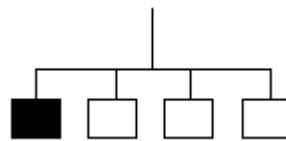
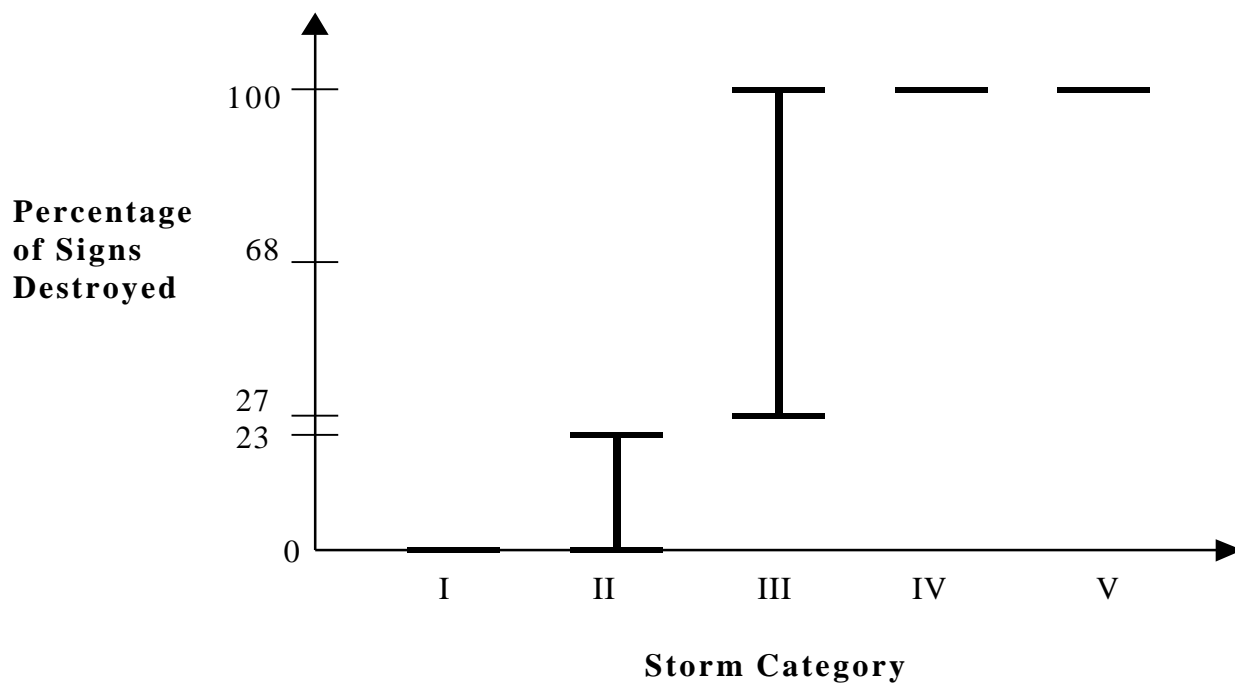
| Minimum Wind Speed (mph) | Median (mph) | Maximum (mph) | Category |
|--------------------------|--------------|---------------|----------|
| 74                       | 86           | 95            | 1        |
| 96                       | 103          | 110           | 2        |
| 111                      | 120.5        | 130           | 3        |
| 131                      | 143          | 155           | 4        |
| 156+                     | -            | -             | 5        |



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# Range of Damage by Category

Extent of Damage



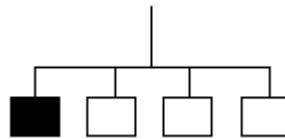
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# Sign Strengthening Alternatives

Extent of Damage

## •Some Possible Alternatives:

- Retrofit all existing equipment to new higher standards.
- Retrofit a given percentage of existing equipment.
- Design all equipment in the future to new much higher (or moderately higher) standards.
- Replace a percentage of existing equipment that is above a given age limit.
- Do nothing.

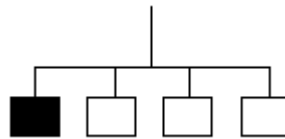


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# Sign Strengthening Alternatives

Extent of Damage

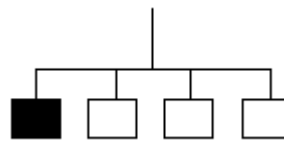
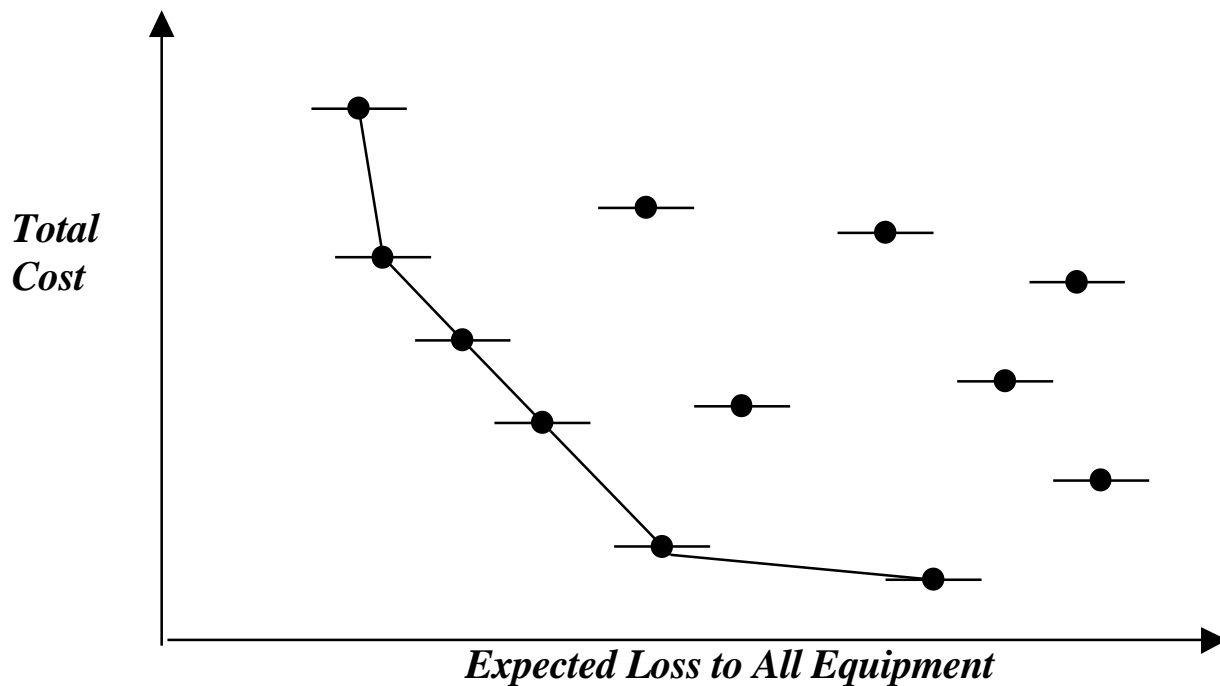
- Elements of model:
  - Cost of retrofit
  - Degree of retrofit
  - Lifetime of equipment
  - Cost of maintenance
  - Wind speeds
  - Hurricane frequencies



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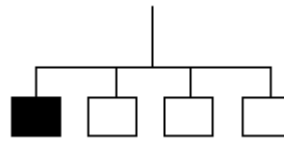
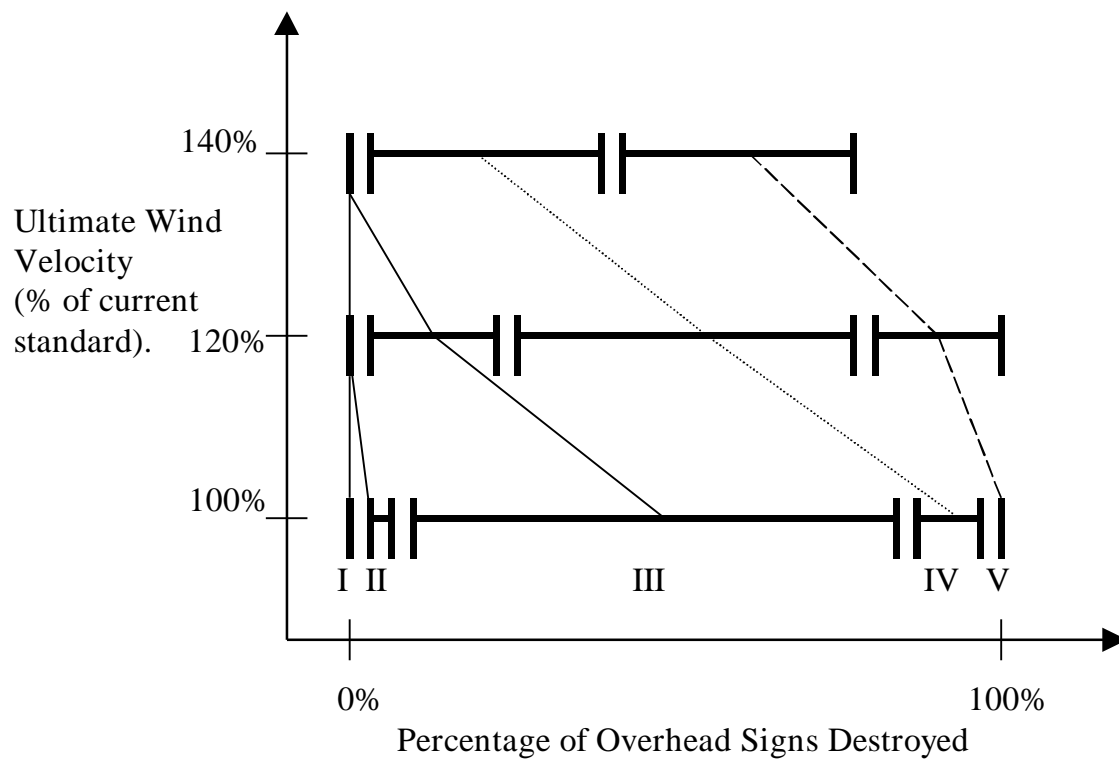
# Trade-off Analysis Tool

Extent of Damage



# Comparison of Strengthening Options

## Extent of Damage

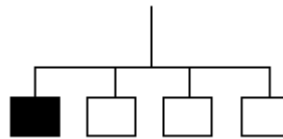


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# Future Work

## Extent of Damage

- Further analysis and application of Ultimate Wind Velocity
- Alternative ways to characterize equipment damage
- Further study of input elements involved in equipment strengthening model

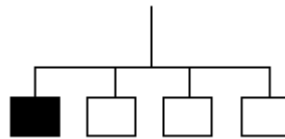


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# Conclusions

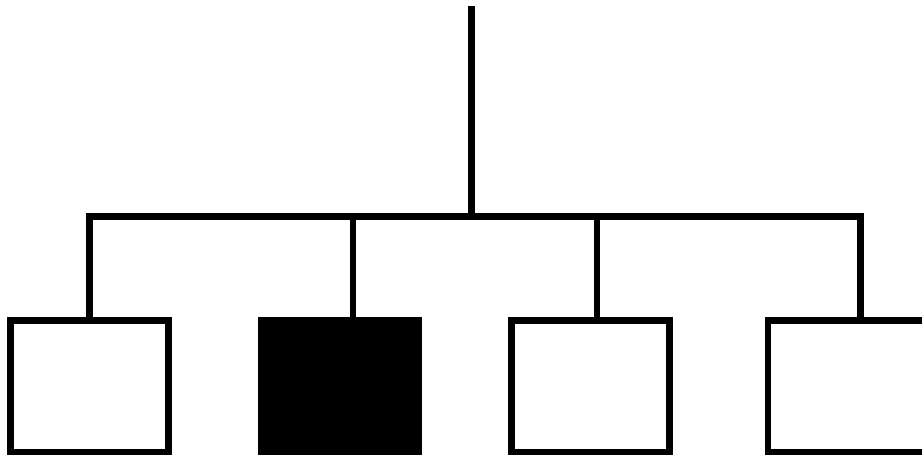
## Extent of Damage

- This approach gives a better understanding of the effects of each hurricane category on damageable highway equipment.
- Cost might be saved in the long run by increasing the equipment standards



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# Spares/Reserves of Aluminum

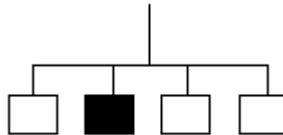


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# Objective

## Spares/Reserves of Aluminum

To provide VDOT with the necessary elements that go into preparing for a full recovery effort of highway signs by conducting analyses of costs and benefits of alternative inventory management

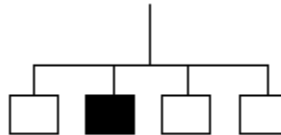


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# Approach

## Spares/Reserves of Aluminum

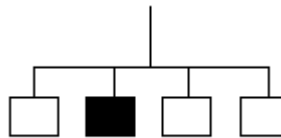
- Number of signs damaged in a hurricane (ft<sup>2</sup> of aluminum)
- Cost of raw materials
- Production and storage costs for VDOT to produce the signs
- Costs to have contractor make the signs



# Analysis

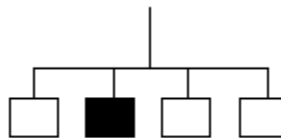
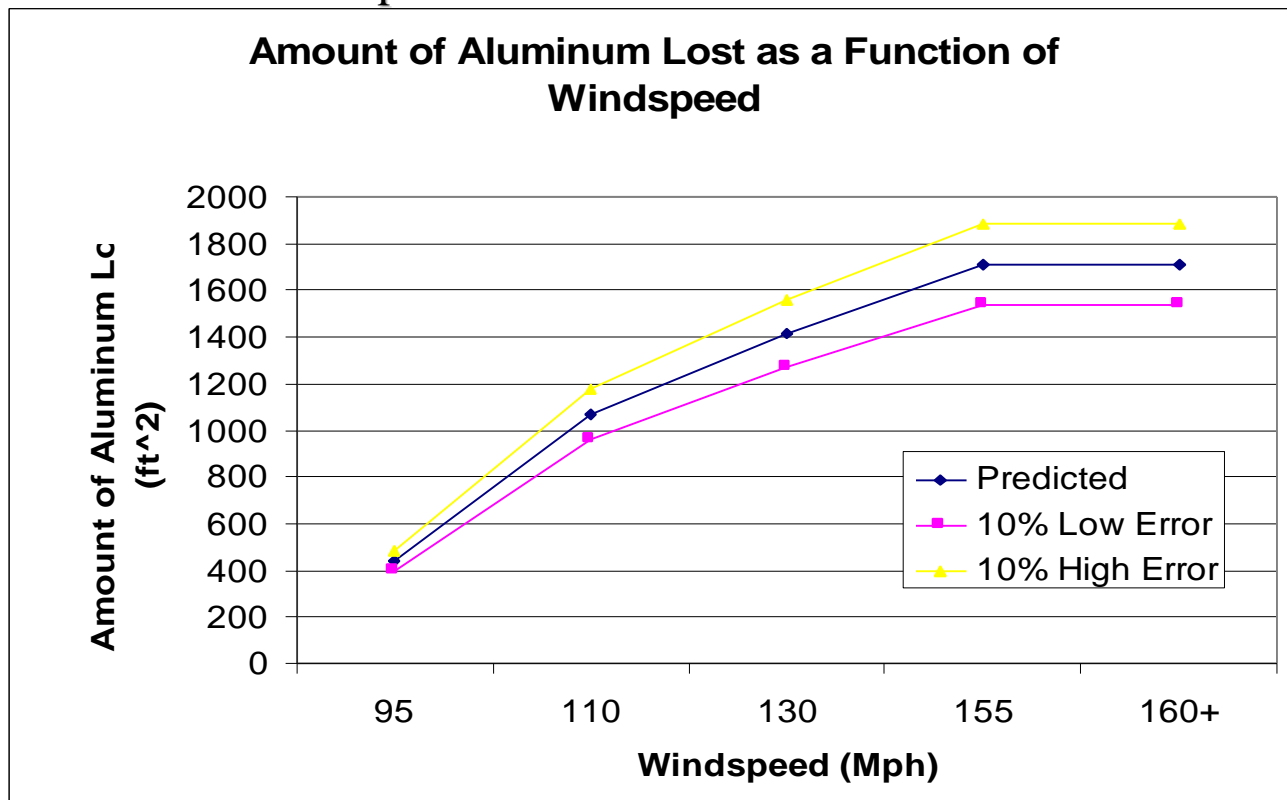
## Spares/Reserves of Aluminum

| Size (W x H)                        | ft <sup>2</sup> | Overhead | Ground  | Cantilever | Total          |
|-------------------------------------|-----------------|----------|---------|------------|----------------|
| 6.00 10.00                          | 60.00           | 2.00     |         | 2.00       |                |
| 3.00 5.00                           | 15.00           |          | 2.00    |            |                |
| 2.00 5.00                           | 10.00           |          | 3.00    |            |                |
| 2.00 2.00                           | 4.00            |          | 30.00   |            |                |
| 1.00 1.50                           | 1.50            |          | 3.00    |            |                |
| 0.75 1.50                           | 1.13            |          | 54.00   |            |                |
| 8.00 10.00                          | 80.00           | 4.00     | 1.00    | 1.00       |                |
| 3.00 3.00                           | 9.00            |          | 15.00   |            |                |
| 2.00 3.00                           | 6.00            |          | 2.00    |            |                |
| 2.50 2.50                           | 6.25            |          | 8.00    |            |                |
| 10.00 14.00                         | 140.00          |          | 2.00    |            |                |
| 4.00 13.00                          | 52.00           |          | 1.00    |            |                |
| 5.00 6.00                           | 30.00           |          | 2.00    |            |                |
| 5.00 10.00                          | 50.00           |          | 3.00    |            |                |
| 1.00 1.00                           | 1.00            |          | 3.00    |            |                |
| 1.00 3.00                           | 3.00            |          | 1.00    |            |                |
| <i>Amount of aluminum</i>           |                 | 440      | 1070.25 | 200        |                |
| <i>Percent Lost in Category 1</i>   |                 | 0.00%    | 41.10%  | 0.00%      |                |
| <i>Percent Lost in Category 2</i>   |                 | 0.00%    | 100.00% | 0.00%      |                |
| <i>Percent Lost in Category 3</i>   |                 | 47.50%   | 100.00% | 68.00%     |                |
| <i>Percent Lost in Category 4</i>   |                 | 100.00%  | 100.00% | 100.00%    |                |
| <i>Percent Lost in Category 5</i>   |                 | 100.00%  | 100.00% | 100.00%    |                |
| <i>Amount of aluminum lost in 1</i> |                 | 0.00     | 439.87  | 0.00       | <b>439.87</b>  |
| <i>Amount of aluminum lost in 2</i> |                 | 0.00     | 1070.25 | 0.00       | <b>1070.25</b> |
| <i>Amount of aluminum lost in 3</i> |                 | 209.00   | 1070.25 | 136.00     | <b>1415.25</b> |
| <i>Amount of aluminum lost in 4</i> |                 | 440.00   | 1070.25 | 200.00     | <b>1710.25</b> |
| <i>Amount of aluminum lost in 5</i> |                 | 440.00   | 1070.25 | 200.00     | <b>1710.25</b> |



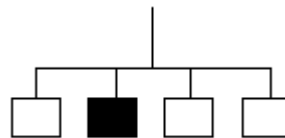
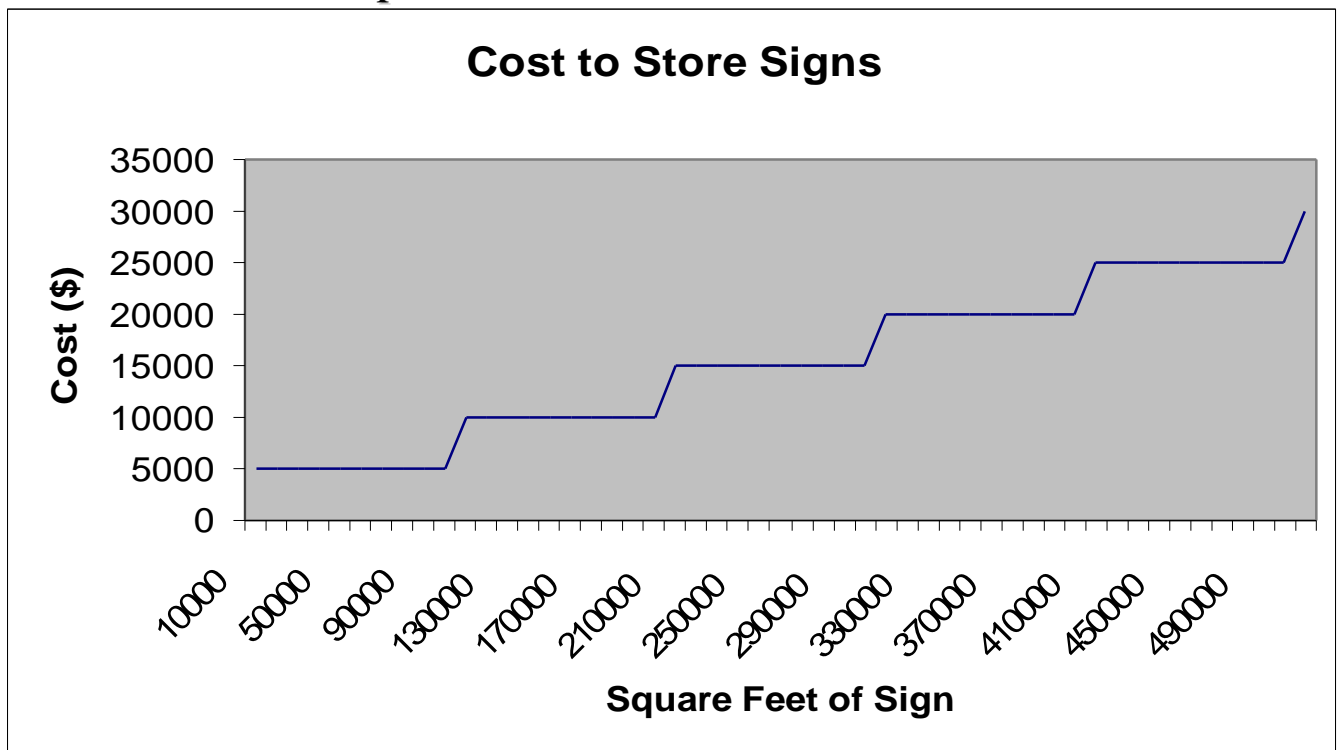
# Analysis (cont.)

## Spares/Reserves of Aluminum



# Analysis (cont.)

## Spares/Reserves of Aluminum



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# Production/Storage Costs to VDOT

$$\text{Total Cost of Material} = M(x) = \$2.0x$$

$$\text{Total Cost of Production} = P(x) = \$17.0x$$

$$\text{Total Cost of Labor} = L(x) = \$0.85x$$

$$\text{Total Cost of Storage} = S(x) = \begin{cases} \$5,000 & \text{if } x \leq 100,000 \\ \$10,000 & \text{if } x \leq 200,000 \\ \dots \end{cases}$$

$x$  = Amount of aluminum lost

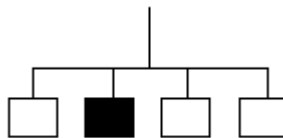


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# Analysis

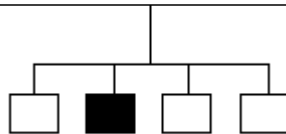
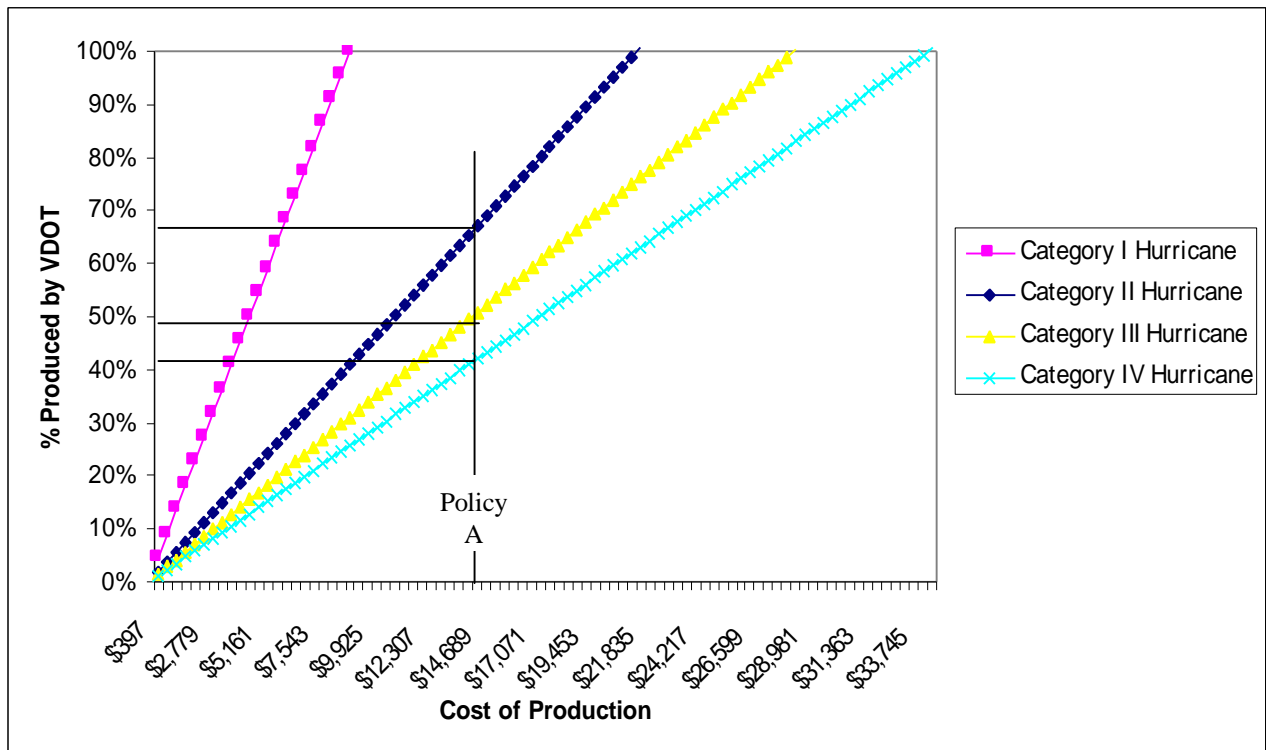
## Spares/Reserves of Aluminum

|             | 0-50       | 51-100 (10% off) | >100 (15% off) |
|-------------|------------|------------------|----------------|
| 6x10 (feet) | \$1,188.60 | \$1,069.74       | \$1,010.31     |
| 3x5         | \$297.15   | \$267.44         | \$252.58       |
| 2x5         | \$198.10   | \$178.29         | \$168.39       |
| 2x2         | \$79.24    | \$71.32          | \$67.36        |
| 1x1.5       | \$29.72    | \$26.75          | \$25.27        |
| 0.75x1.5    | \$22.29    | \$20.07          | \$18.95        |
| 8x10        | \$1,584.80 | \$1,426.32       | \$1,347.08     |
| 2x3         | \$118.86   | \$106.98         | \$101.04       |
| 3x3         | \$178.29   | \$160.47         | \$151.55       |
| 2.5x2.5     | \$123.82   | \$111.44         | \$105.25       |
| 10x13       | \$2,575.30 | \$2,317.77       | \$2,189.00     |
| 4x13        | \$1,030.12 | \$927.11         | \$875.60       |



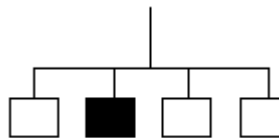
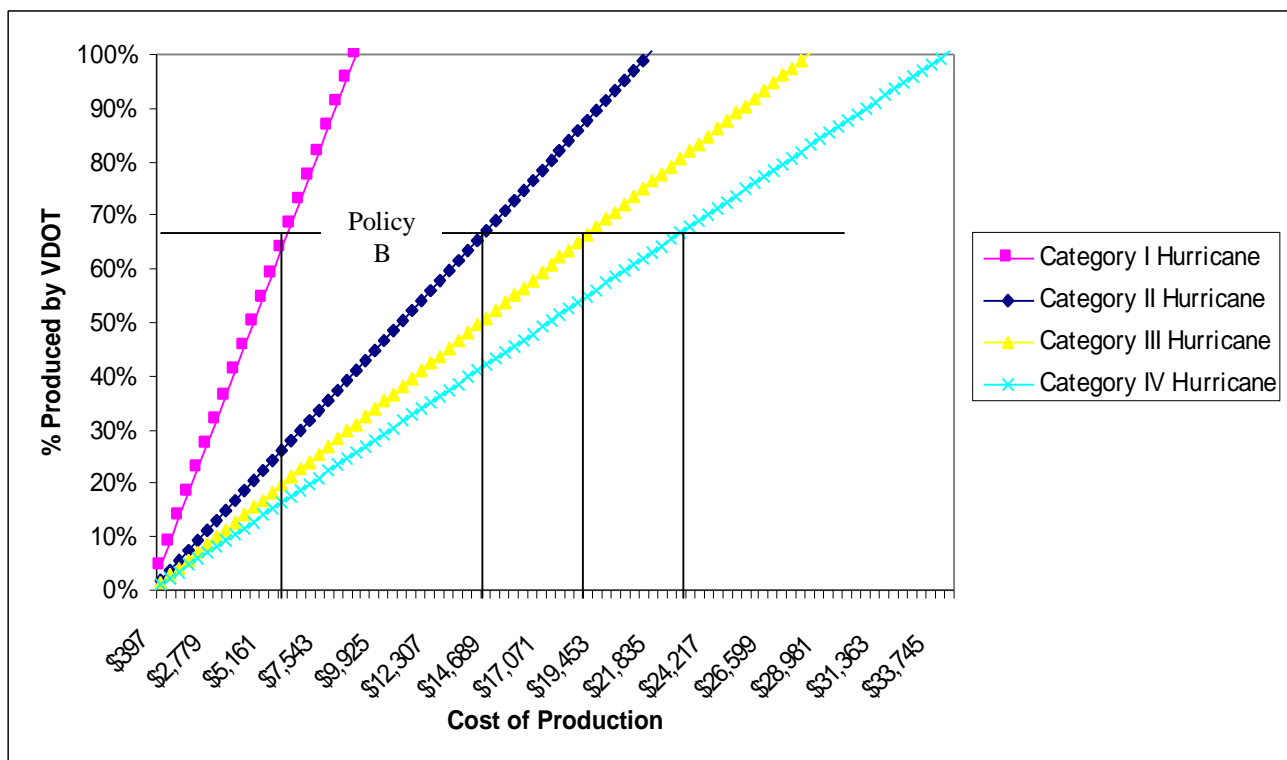
# Setting Sign-Inventory Policy

## Spares/Reserves of Aluminum



# Sign-Inventory Policy (cont.)

## Spares/Reserves of Aluminum

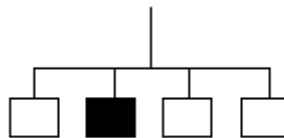


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# Future Work

Spares/Reserves of Aluminum

- Apply to analysis to entire Suffolk District
- Explore diversity of policy options
- Decide on policy that best provides for the community and the state

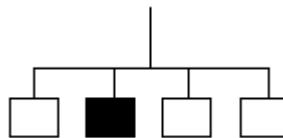


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# Conclusions

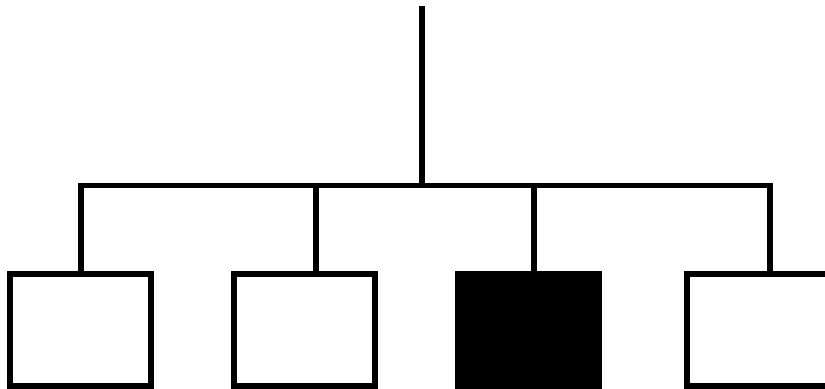
## Spares/Reserves of Aluminum

- Provide to VDOT the elements necessary to set a policy for recovery
- Help VDOT set a policy for inventory and hurricane preparedness in terms of the replacement of highway signs



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# Critical Replacement of Damaged Equipment

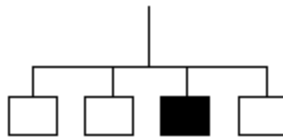


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# Objective

## Priority Setting

The goal of this approach is to provide a methodology for establishing priorities for the order of the long-term recovery of road segments in the Suffolk District.

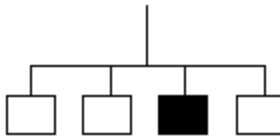


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# Overview of Approach

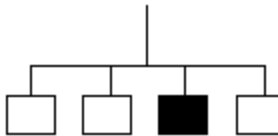
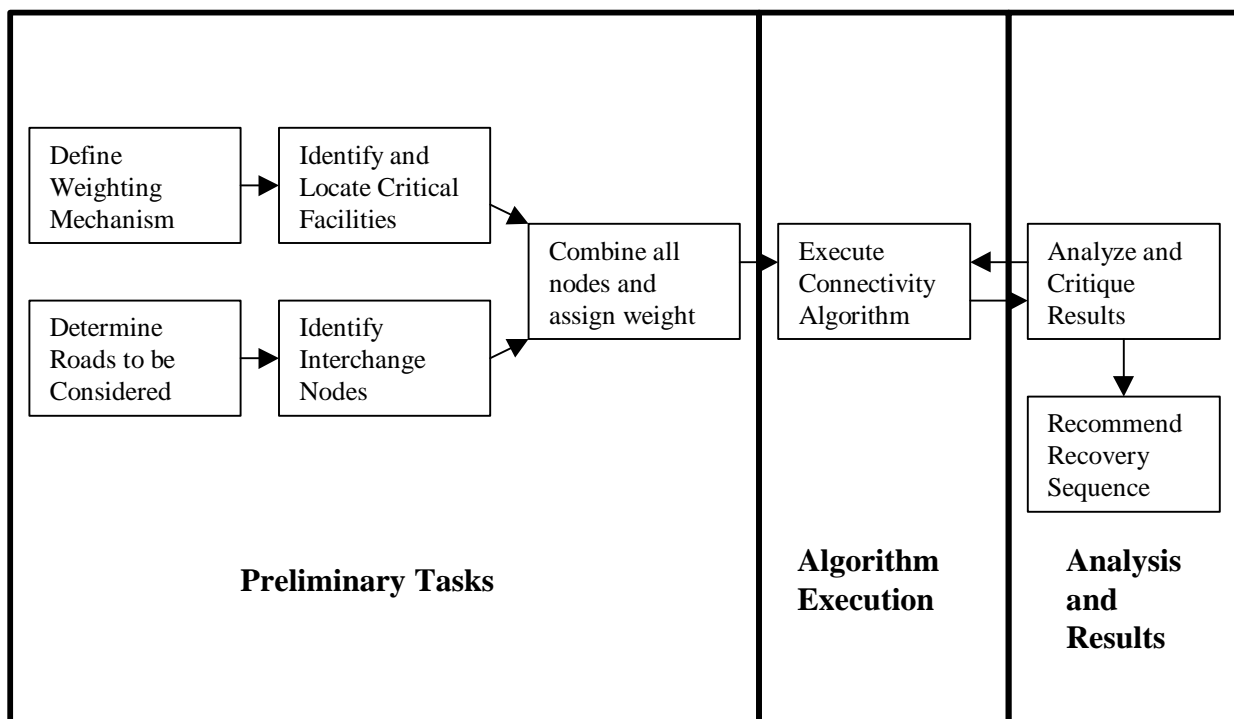
## Priority Setting

- Introduction
- Technical approach
  - Network development
  - Connectivity algorithm
  - Algorithm execution
    - Three methods of execution
- Results
- Conclusions



# Overview of Approach (cont.)

## Priority Setting

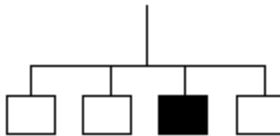


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# Network Development

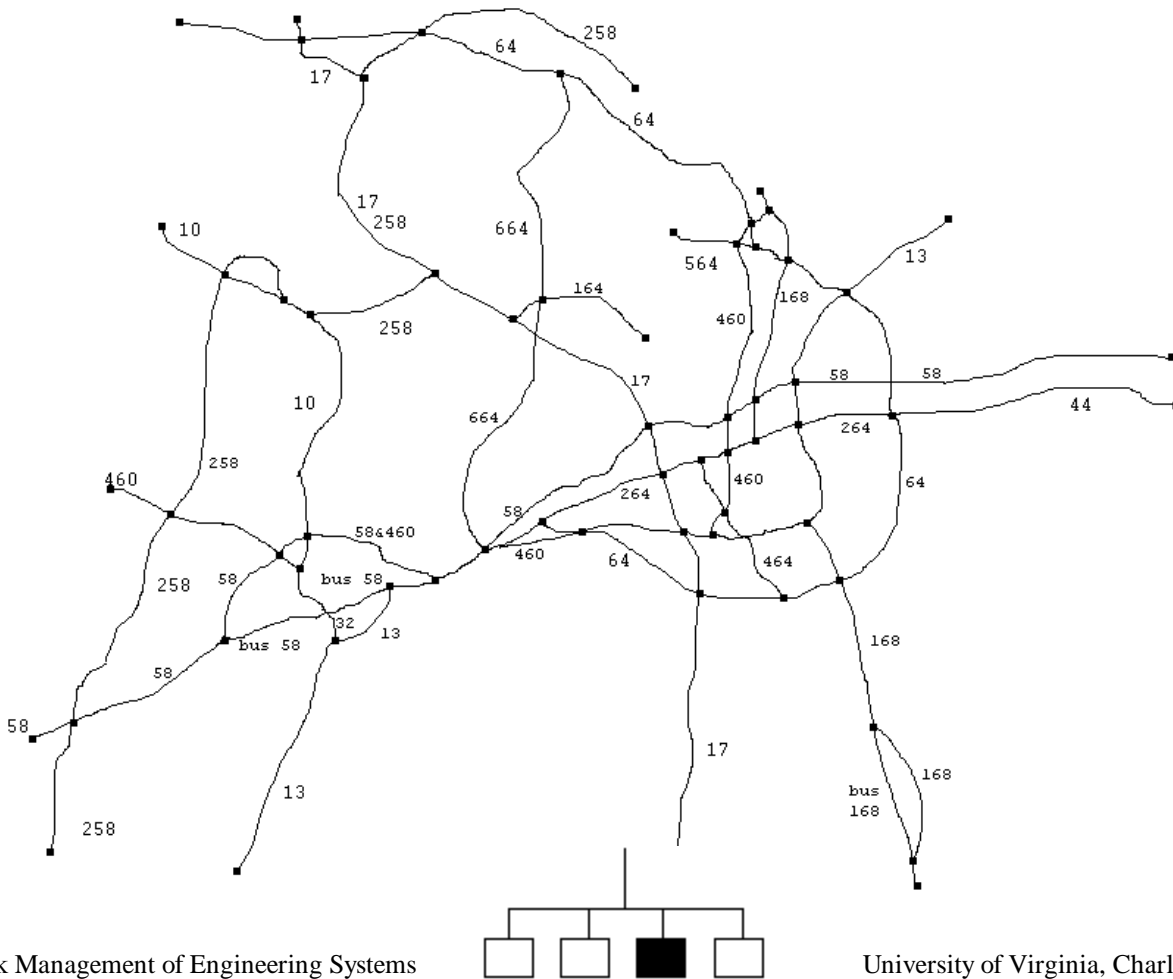
## Priority Setting

- Network defined for Suffolk highways
  - A set of interchanges connected by one or more road segments
- Road establishment
- Node establishment
  - Intersection nodes
  - Additional nodes....



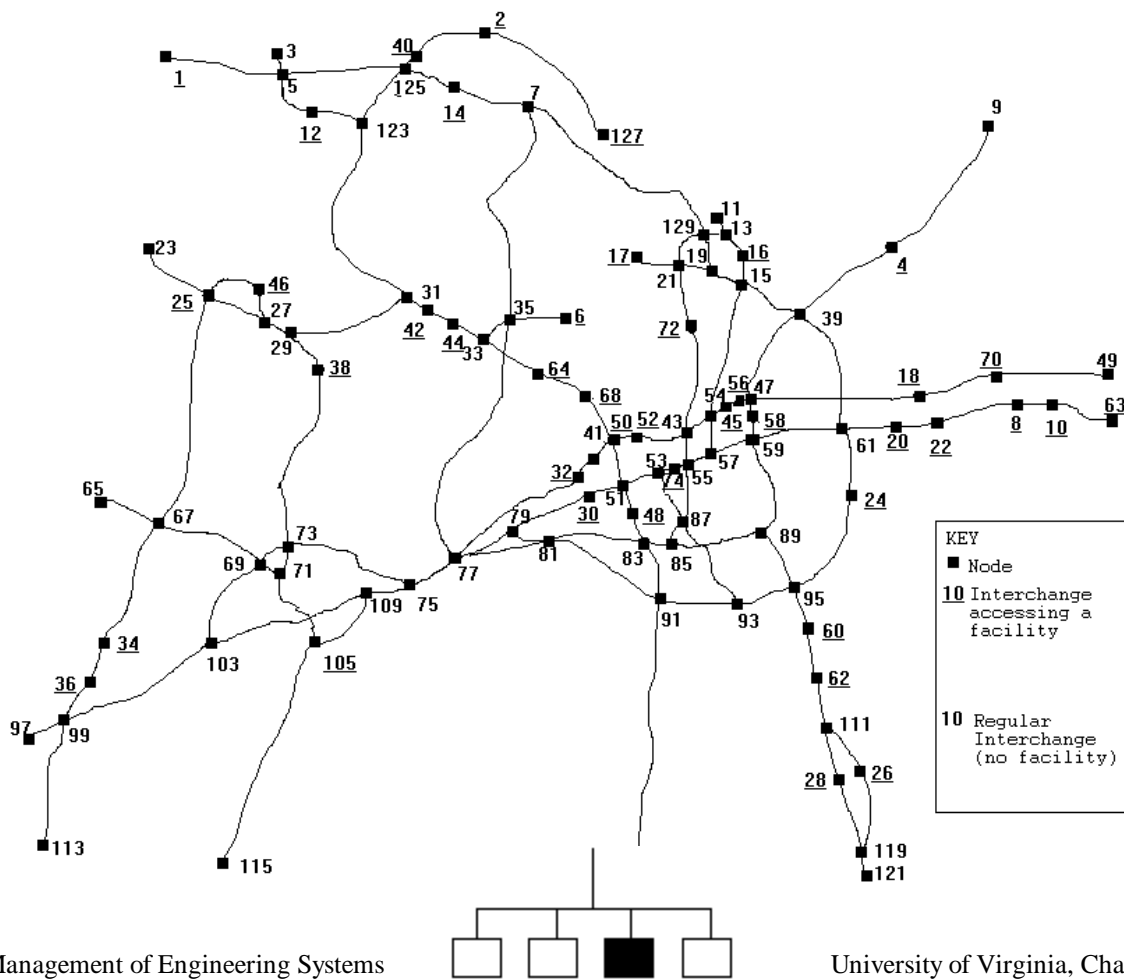
# Network With Road Labels

## Priority Setting



# Network With Node Labels

## Priority Setting

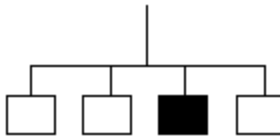


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# Connectivity Algorithm

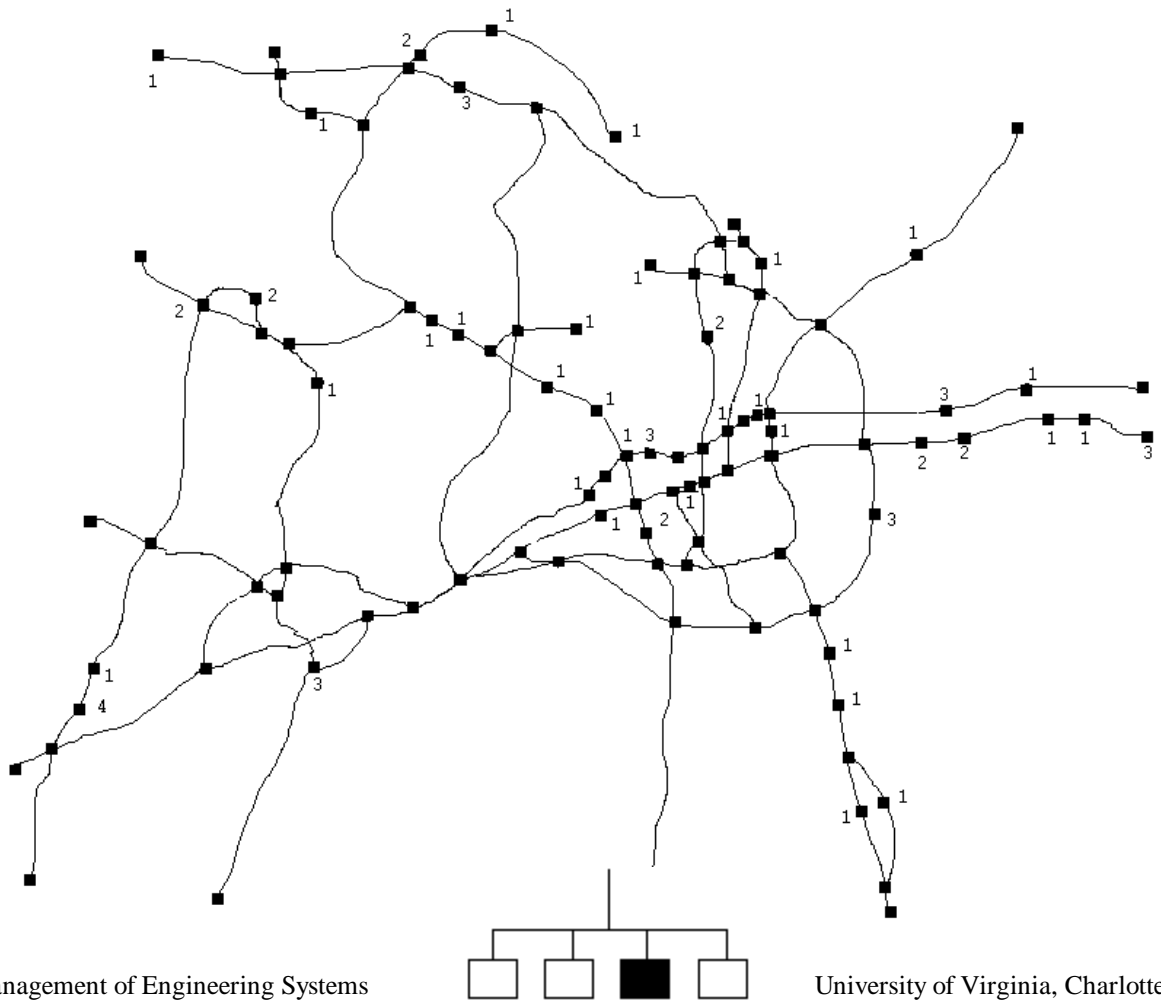
## Priority Setting

- Node weighting mechanisms
  - Our choice: Critical facilities
  - Other options
- Connectivity defined
  - Sum of number of paths connecting any two weights



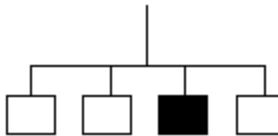
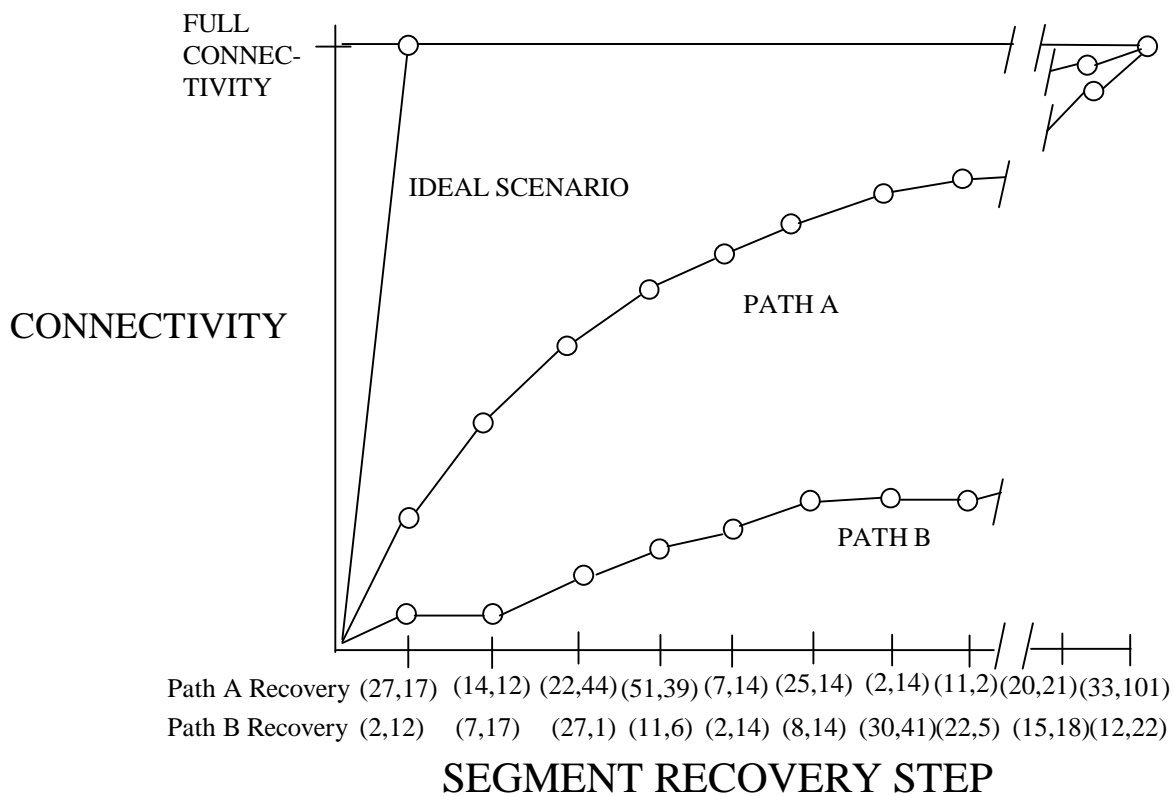
# Model Network with Weights

## Priority Setting



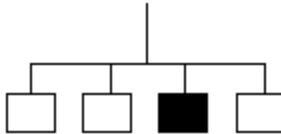
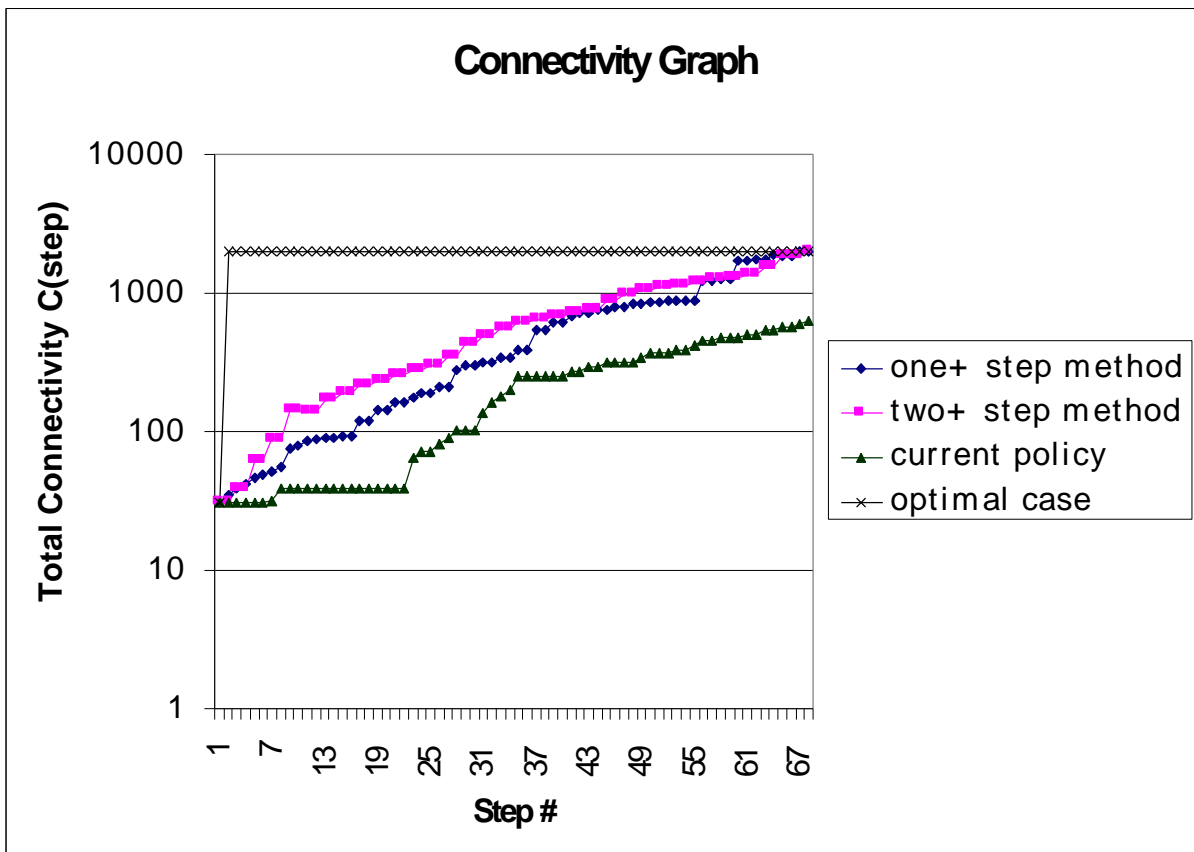
# Goals of the Algorithm

## Priority Setting



# Efficiency of the Recovery

## Priority Setting



# Steps to Recovery

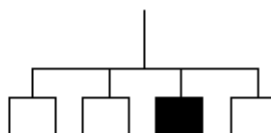
## Priority Setting

- Two+ Step method is superior

| 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   |

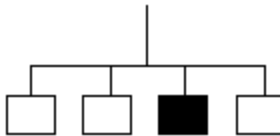


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# Conclusions

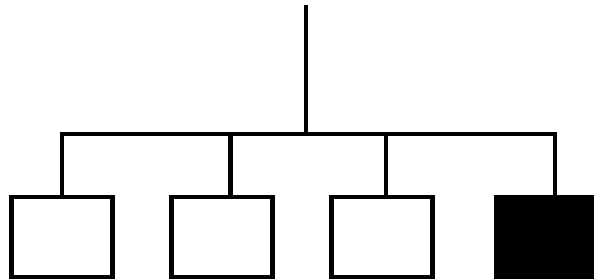
## Priority Setting

- Variations in weighting
  - Traffic volumes
  - Population densities
- Variations in applications
  - Recovery from any disaster type
  - Applicable to any network where node weight can be an attribute



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# Time-to-Recovery

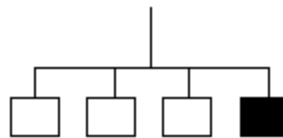


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# Objective

Time-to-Recovery

The goal of this approach is to analyze the VDOT recovery/repair process following a hurricane to identify critical tasks and reduce the time-to-recovery

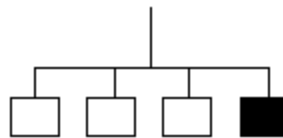


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# Approach

Time-to-Recovery

- Identify sign recovery and activity sequence
- Critical path analysis
- Uncertainties in the critical path
- Time-cost tradeoffs
- Future work
  - simulation and modeling

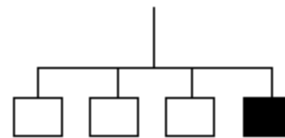


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# Sequence of Activity Setup

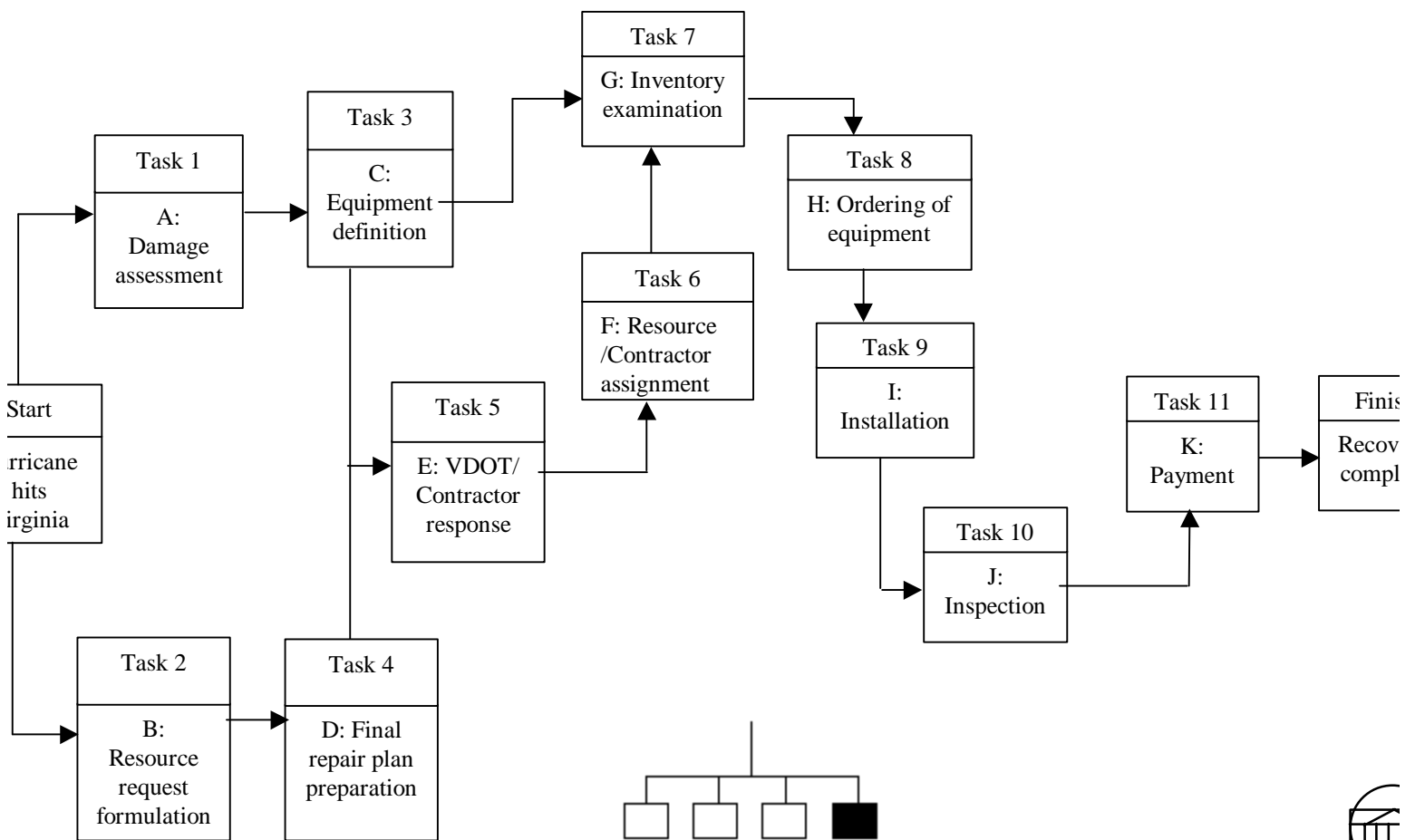
## Time-to-Recovery

| Activity | Number | Description  | Immediate Predecessor(s) |
|----------|--------|--|--------------------------|
| A        | 1      | Damage assessment conducted  | None                     |
| B        | 2      | Requests for resources formulated  | None                     |
| C        | 3      | Equipment that must be replaced is defined   | A                        |
| D        | 4      | Final repair plans prepared  | B                        |
| E        | 5      | Plans and schedules disbursed and responses obtained from VDOT inventories/contractors | C, D                     |
| F        | 6      | Resources and contractors assigned to damaged areas                                    | E                        |
| G        | 7      | Contractors examine inventory  | C, F                     |
| H        | 8      | Contractors place order/manufacture equipment  | G                        |
| I        | 9      | Install equipment  | H                        |
| J        | 10     | VDOT conducts inspections  | I                        |
| K        | 11     | Contractors paid   | J                        |



# Recovery Flow

## Time-to-Recovery

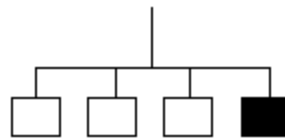


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# Recovery Analysis

Time-to-Recovery

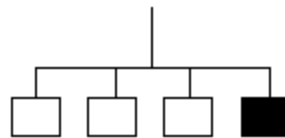
- Estimating Activity Times
  - Most optimistic
  - Most likely
  - Most pessimistic
- Calculating time statistics
  - Expected time
  - Variance



# Recovery Analysis (cont.)

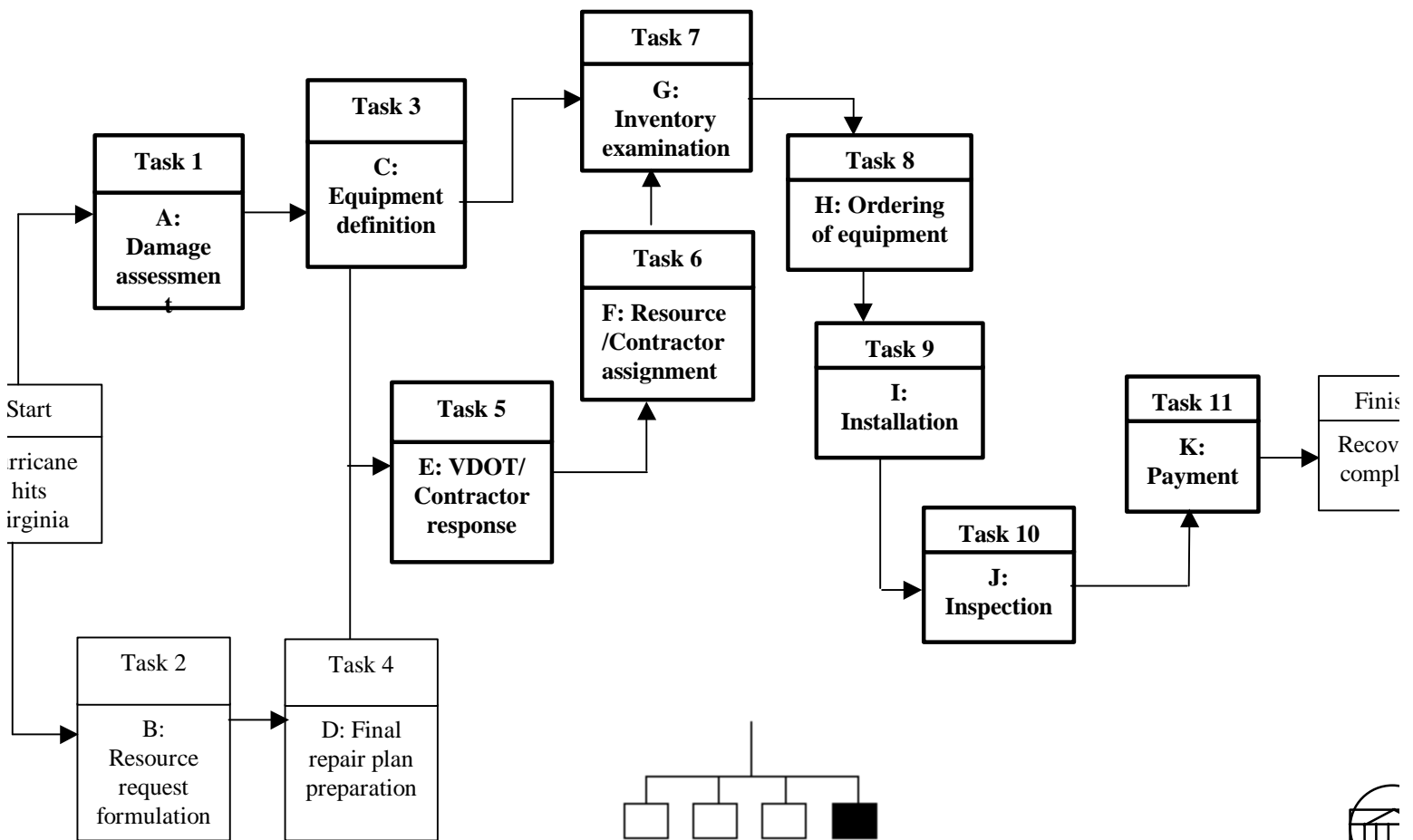
## Time-to-Recovery

| Activity                           | Time Estimates (weeks) |                 |                      | Activity Statistics |          |
|------------------------------------|------------------------|-----------------|----------------------|---------------------|----------|
|                                    | Most optimistic (a)    | Most likely (m) | Most pessimistic (b) | Expected time       | Variance |
| Damage assessment                  | 2                      | 3               | 4                    | 4                   | 0.17     |
| Resource request formulation       | 1                      | 2               | 3                    | 2                   | 0.17     |
| Equipment definition               | 1                      | 2               | 3                    | 2                   | 0.17     |
| Final repair plan preparation      | 1.5                    | 2               | 3                    | 2.1                 | 0.06     |
| Response from VDOT                 | 2                      | 3               | 5                    | 3.2                 | 0.25     |
| Inventory and contractors          |                        |                 |                      |                     |          |
| Resource and contractor assignment | 1                      | 2               | 3                    | 2                   | 0.17     |
| Inventory examination              | 1                      | 1.5             | 2                    | 1.5                 | 0.06     |
| Ordering equipment                 | 2                      | 4               | 6                    | 4                   | 0.17     |
| Installation                       | 5                      | 6               | 10                   | 6.5                 | 0.7      |
| Inspection                         | 2                      | 3               | 4                    | 3                   | 0.17     |
| Payment                            | 3                      | 4               | 5                    | 4                   | 0.17     |



# Recovery Flow with Critical Activities

Time-to-Recovery

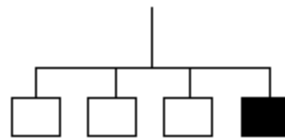
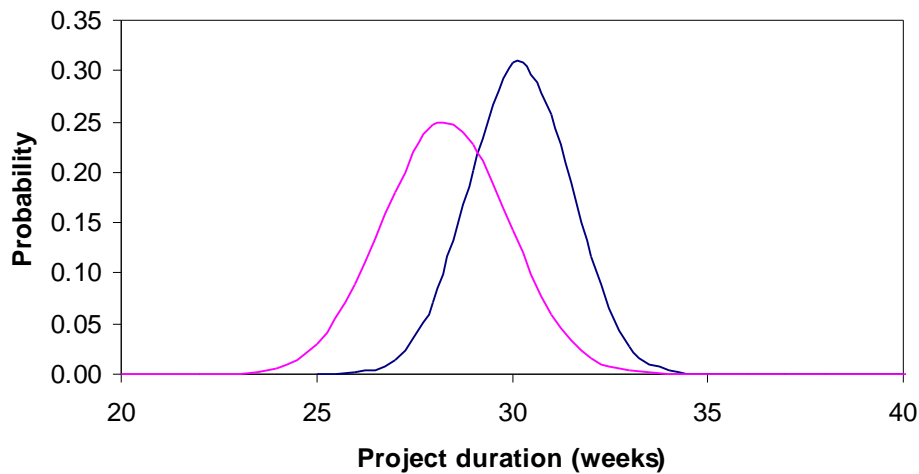


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# Completion Uncertainties (contd.)

## Time-to-Recovery

- Recovery involves uncertainty
- Change in critical path can change the completion time

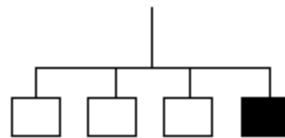


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# Time-Cost Tradeoffs

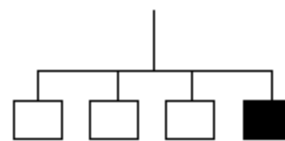
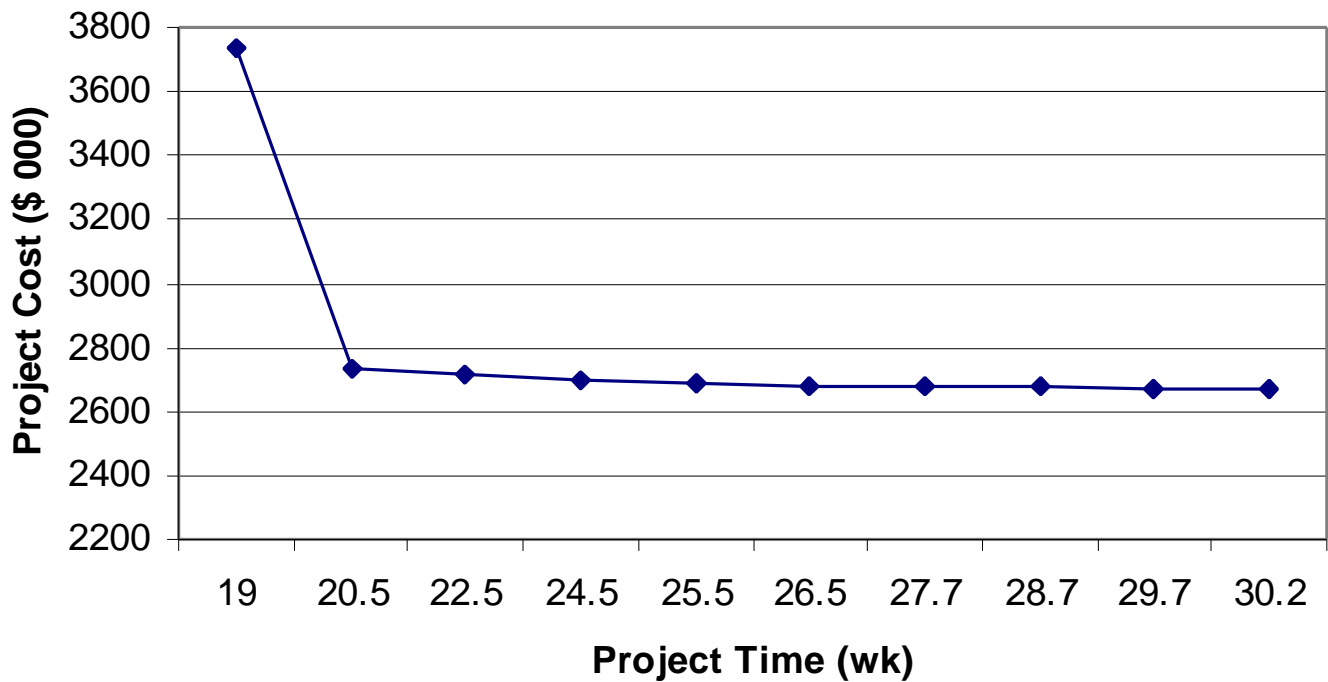
Time-to-Recovery

- Baseline Time ( $b_t$ )
  - Baseline Cost ( $b_c$ )
- Accelerated Time ( $a_t$ )
  - Accelerated Cost ( $a_c$ )



# Time-Cost Tradeoffs (contd.)

Time-to-Recovery

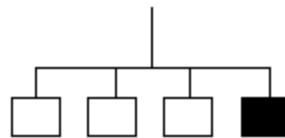


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# Future Work

Time-to-Recovery

- Simulate the installation procedure
  - repair crew picks up replacement equipment
  - travels to highway location
  - replaces/repairs equipment
  - return to sign shop base
  - home base replenishes crew material

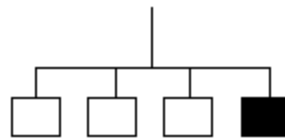


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# Conclusions

## Time-to-Recovery

- Recovery highly dependent on many activities being completed on time
- Activities on the critical path can be accelerated without significant increase in cost
- Installation is the lengthiest and the most variable activity



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# Conclusions and Recommendations



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# Need for Recovery Management

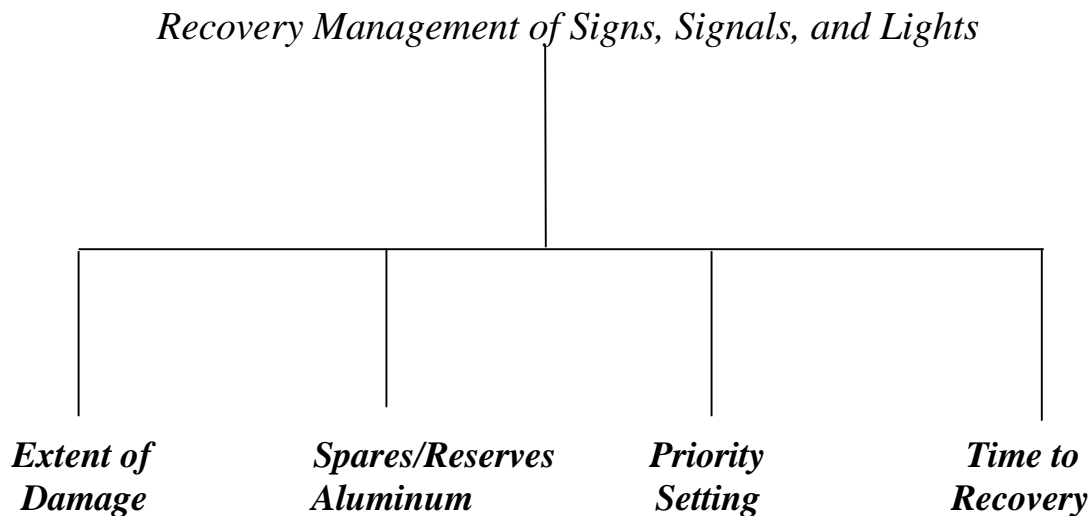
- Questions about state-of-readiness of Virginia stemmed from 1997 Hurricane Workshop
- Suffolk district economy and population have grown extensively in past 15 years
- Suffolk is particularly susceptible to hurricane strikes
- Six hurricanes predicted to form in the Atlantic Ocean this summer. Two of them predicted to be intense storms with wind speeds over 110 mph.



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# Four Approaches

- Four major issues associated with recovery were identified and determined to be beneficial to the overall analysis of hurricane preparedness.



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# Applicability and National Interest

- Help VDOT and FEMA plan efficiently for hurricane recovery
- Example to other states and countries for hurricane recovery management



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# Applicability Across VDOT

- Systems modeling in support of cost/risk-benefit analysis
- All types of disaster planning including flooding, fires, and hazardous material cleanups



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# Recommendations for Future Work

- Outline directions for in-depth analysis in any or all the four issues.
- Statement of work based on these preliminary analyses

