USE OF FORECASTING FOR RESERVES OF VULNERABLE EQUIPMENT

Introduction

This section starts by explaining the motivation of the study, which includes a discussion of hurricanes, historical data, and landfalling data of hurricanes in Virginia. This includes specifying regional damages caused by hurricanes, especially to traffic control equipment. The second part of this section details the structure and the content of each section. The third part of this section discusses the different sources that were researched in order to accomplish this portion of the report. The literature review examines the sources that were studied in order to understand inventory practices, hurricane forecasting, and hurricane behavior.

Problem Definition

The National Hurricane Center (NHC) utilizes the Saffir-Simpson hurricane intensity scale, see Table 3.1, (Simpson and Riehl, 1981) for the Atlantic and Northeast Pacific basins to give an estimate of the potential flooding and damage to property given a hurricane's estimated intensity. The strength of sustained wind speeds can cause considerable regional damage. The greater the sustained wind speeds the greater the damage. Table 6.1.1 shows the range of potential hurricane damage.

Table 6.1.1. Potential Hurricane Damage Classification (Landsea, 1999)

Cat.	Level	Description	Example
1	Minimal	Damage primarily to shrubbery, trees, foliage, and unanchored homes. No real damage to other structures. Some damage to poorly constructed signs. Low-lying coastal roads inundated, minor pier damage, some small craft in exposed anchorage torn from moorings.	Hurricane Jerry (1989)
2	Moderate	Considerable damage to shrubbery and tree foliage; some trees blown down. Extensive damage to poorly constructed signs. Coast roads and low-lying escape routes inland cut by rising water 2 to 4 hours before arrival of hurricane center. Considerable damage to piers. Marinas flooded. Evacuation of some shoreline residences and low-lying areas required.	Hurricane Bob (1991)
3	Extensive	Foliage torn from trees; large trees blown down. Practically all poorly constructed signs blown down. Some damage to roofing materials of buildings; some wind and door damage. Serious flooding at coast and many smaller structures near coast destroyed; larger structures near coast damaged by battering waves and floating debris. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Flat terrain 5 feet of less above sea level flooded inland 8 miles or more. Evacuation of low-lying residences within several blocks of shoreline possibly required.	Hurricane Gloria (1985)
4	Extreme	Shrubs and trees blown down; all signs down. Flat terrain 10 feet of less above sea level flooded inland as far as 6 miles. Major damage to lower floors of structures near shore due to flooding and battering by waves and floating debris. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Major erosion of beaches. Massive evacuation of all residences within 500 yards of shore possibly required, and of single-story residences within 2 miles of shore.	Hurricane Andrew (1992)
5	Catastrophic	Shrubs and trees blown down; considerable damage to roofs of buildings; all signs down. Major damage to lower floors of all structures less than 15 feet above sea level within 500 yards of shore. Low-lying escape routes inland cut by rising water 3 to 5 hours before hurricane center arrives. Massive evacuation of residential areas on low ground within 5 to 10 miles of shore possibly required.	Hurricane Camille (1969)

Hurricanes are natural events that can have catastrophic results. The National Hurricane Center (NHC) has reported that the mean annual damage caused by hurricanes in mainland U.S. is $4,800,000,000 over the past 75 years (NHC, 1999).

Pielke and Landsea (1998) calculated the damage caused by various categories of U.S. landfalling tropical storms and hurricanes after normalization by the inflation rate, increases in wealth, and coastal population changes. Damages incurred as a result of tropical cyclones occurring between 1925 through 1995 were tabulated in terms of 1995 U.S. dollars. Table 6.1.2 summarizes the findings:

Table 6.1.2. Median Damage Costs of US Landfalling Tropical Storms and Hurricanes from 1925-1995 (Pielke and Landsea,1998)

Intensity	Cases	Median Damage (1995 $)	Potential Damage *
Tropical/Subtropical Storm	118	Less than $1,000,000	0
Hurricane Category 1	45	$33,000,000	1
Hurricane Category 2	29	$336,000,000	10
Hurricane Category 3	40	$1,412,000,000	50
Hurricane Category 4	10	$8,224,000,000	250
Hurricane Category 5	2	$5,973,000,000	500

* The "Potential Damage" provides a reference value if one assigns the median damage caused by a Category 1 Hurricane to be "1". The rapid increase in damage observed as the categories increase is apparent. (The value for Category 5 Hurricanes may not be representative of true amounts because of the very small sample available.)

According to Table 6.1.2 if the potential damage caused by a Category 1 Hurricane serves as the standard unit by which potential damage is calculated, the a Category 5 Hurricane causes 250 times more damaged than a Category 1 Hurricane.

The United States is vulnerable to tropical cyclones (TC) now more than ever, as millions of people have populated the coastlines, making more people and residences exposed to cyclone winds, rain, storm surge, and severe weather. During this century, improved forecasts and more public awareness have aided in the effort to reduce loss of life and damage to communities.

The East Coast and the southern states along the Gulf of Mexico are the regions that are most likely to get hit by a hurricane. According to the National hurricane Center (NHC), the United States mainland from 1900-1996 has been struck by hurricanes over 158 times; 64 of these storms have been hurricanes of categories 3, 4, and 5 hurricanes. As shown in Table 6.1.3, Virginia has been struck only by four hurricanes.

Table 6.1.3. U.S. Mainland Hurricane Strikes by States, 1900-1996 (NHC, 1999)

Area	Category Number					All	Major
	1	2	3	4	5	1,2,3,4,5	3,4,5
U.S. Texas to Maine	58	36	47	15	2	158	64
Texas	12	9	9	6	0	36	15
Louisiana	8	5	8	3	1	25	12
Mississippi	1	1	5	0	1	8	6
Alabama	4	1	5	0	0	10	5
Florida	17	16	17	6	1	57	24
Georgia	1	4	0	0	0	5	0
South Carolina	6	4	2	2	0	14	4
North Carolina	10	4	10	1	0	25	11
Virginia	2	1	1	0	0	4	1
Maryland	0	1	0	0	0	1	0
Delaware	0	0	0	0	0	0	0
New Jersey	1	0	0	0	0	1	0
New York	3	1	5	0	0	9	5
Connecticut	2	3	3	0	0	8	3
Rhode Island	0	2	3	0	0	5	3
Massachusetts	2	2	2	0	0	6	2
New Hampshire	1	1	0	0	0	2	0
Maine	5	0	0	0	0	5	0

Though the hurricanes in Virginia have been minor, the NHC suggests that weather patterns have been changing and more severe hurricanes can affect more of the northern states.

According to the National Oceanic and Atmospheric Administration (NOAA), the Suffolk District of Virginia has been affected by five minor hurricanes between 1900 and 1996. Figure 6.1.1 illustrates the hurricane landfalls from 1900-1996 for the Suffolk District.

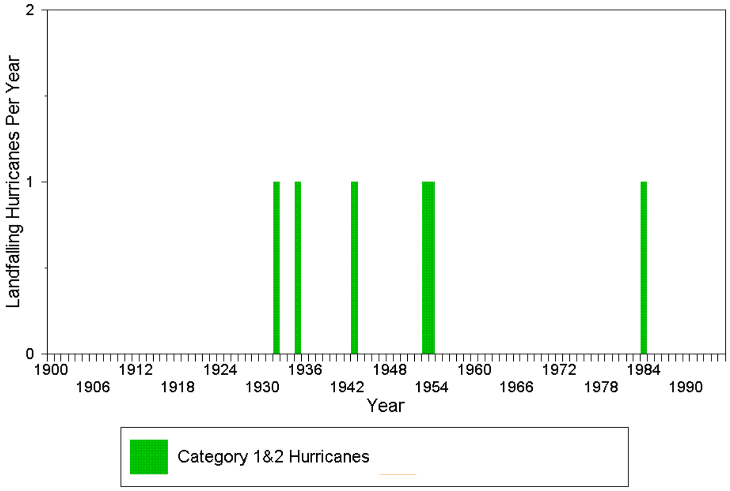

Figure 6.1.1. Suffolk County Hurricane Landfall from 1900-1996 (Landsea,1999)

The NHC also provides historical information regarding the occurrence of major hurricanes have on the mainland US coastline. The NHC states that the major hurricane season is between June and November. Most of the strikes occur from the middle of August to the end of October as seen in Figure 6.1.2. Figure 6.1.2 shows the months that a hurricane occurred, from 1885 and 1996.

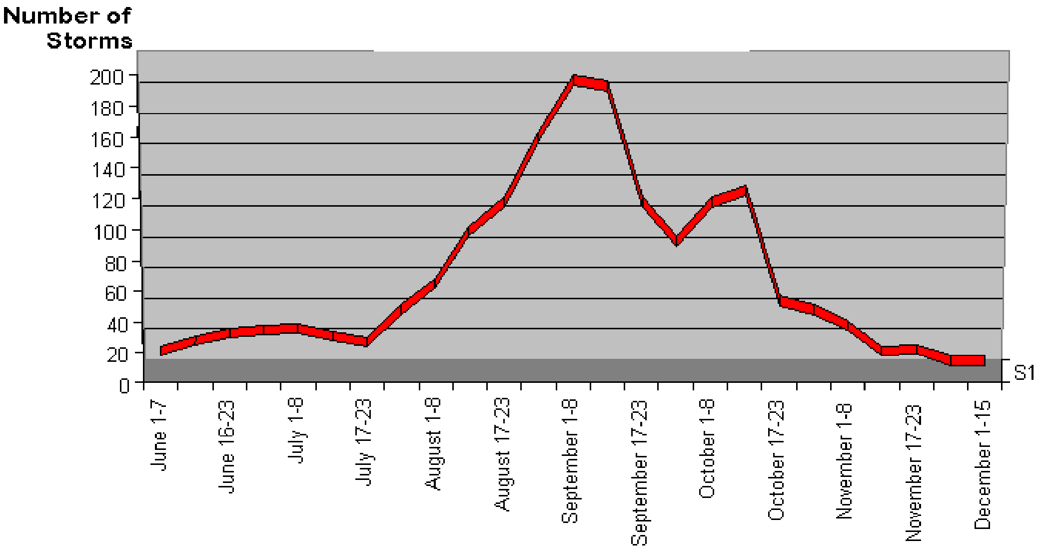

Figure 6.1.2. Historical Data of Monthly Hurricane Landfalls from 1885-1996 (FEMA,1999)

Table 6.1.4 details all major hurricane direct hits to the U.S. coastline from 1900 to 1996.

Table 6.1.4. Major Hurricane Direct Hits on Mainland US Coastline and for Individual States, 1900-1996 by Month (NHC, 1999)

Area	June	July	Aug.	Sept.	Oct.	All
U.S. Texas to Maine	2	3	15	36	8	64
Texas	1	1	7	6	0	15
Louisiana	2	0	4	5	1	12
Mississippi	1	1	5	0	1	6
Alabama	0	1	0	4	0	5
Florida	0	1	2	15	6	24
Georgia	0	0	0	0	0	0
South Carolina	0	0	0	3	1	4
North Carolina	0	0	2	8	1	11
Virginia	0	0	0	1	0	1
Maryland	0	0	0	0	0	0
Delaware	0	0	0	0	0	0
New Jersey	0	0	0	0	0	0
New York	0	0	1	4	0	5
Connecticut	0	0	1	2	0	3
Rhode Island	0	0	1	2	0	3
Massachusetts	0	0	0	2	0	2
New Hampshire	0	0	0	0	0	0
Maine	0	0	0	0	0	0

Despite such historical records, hurricanes are unpredictable. It is difficult to predict the day and intensity of their strikes, how long they will last and the extent of damage. One of the most widely used tracking models is CLIPER, which gives a warning only 72 hours before a hurricane strikes, meaning that there are only three days to prepare (Landsea, 1999). Such short advance warning does not allow enough time to obtain all the resources required to recover from such a disaster. However, some studies are being conducted to generate seasonal forecasts for the next hurricane season as early as December.

Hurricanes threaten human safety and traffic infrastructure. Hurricane Andrew, a Category 4 Hurricane, struck Florida in 1993 and caused extensive damages to signs, signals and lights (NCEP, 1999). According to Florida Department of Transportation (FDOT), hurricane Andrew caused the following damages to highway traffic equipment in County No. 6 in Miami County, Florida (Fassrainer and Santana, 1999):

Table 6.1.5. Damage Caused to Traffic-Control Equipment by Hurricane Andrew to County No. 6. Miami County, Florida

EQUIPMENT	DAMAGE
Signals	
Heads	2,000 (400 intersections)
Signs	
Overhead Structure	7
Multiple post ground-mounted signs	45
Single post ground-mounted signs	169
Span-wire attached signs	5

As observable from the information in Table 6.1.5, the equipment that suffered the most damage were ground-mounted signs and signal heads.

Another example of the extent of damage a hurricane can cause to highways can be best described by the costs that North Carolina experienced with Hurricane Fran (Category 3). Damages to public property (debris removal, damages to roads and bridges, etc.) in North Carolina were estimated to be approximately $1.1 billion (NOAA, 1999).

The tidewater region with a population of approximately 900,000 people is one of the most populated areas in Virginia, and because it is on the coast it, is vulnerable to hurricane activity (US Census Bureau, 1998). Several historical landmarks are in the Tidewater region. Also, tourism is very prominent in the coastal area.

Impairment of traffic-control equipment reduces the ability to transport people, equipment, and resources needed for the restoration of infrastructure. Without signs to direct travelers and lights to illuminate roads, highways can be confusing and dangerous places. Businesses, government, and educational centers will remain closed until some level of recovery is achieved. Months or even years could pass before a community can recover to its original state in terms of traffic control equipment. A community cannot return to daily activities when its road system is not functional. Though aid from the federal government could be expected through FEMA and FHWA, these funds can take months to be received and require detailed accounting of reimbursable expenditures by local agencies.

Due to the criticality of traffic-control systems, a major concern for VDOT is the potential damage to highway signs, signals, and lights. In order to repair the damaged signs, signals and lights, VDOT should determine an adequate level of reserves in advance of such disaster.

Managing the required quantities of reserves of signs, signals and lights to be prepared in case of a hurricane is a difficult task. One has to be able to find an appropriate level of reserves that keeps costs low but still aids in an expeditious recovery in case of a hurricane.

Reserves have to be maintained at a level that allows an initial effort of recovery. Furthermore, months after a hurricane, a well-chosen level of reserves will enable a steady recovery. Having an initial but substantial amount of reserves can permit enough time for production (sign shops) to supply the amounts of signs, signals and lights that are still required for the months ahead.

A decision whether to increase reserves prior to a hurricane affecting the area could be critical. The levels of reserves for the Tidewater region are determined largely according to patterns observed in previous years. VDOT does not currently increase levels of traffic equipment reserves during hurricane season.

VDOT, in order to meet the demands of reserves for the state of Virginia, has three regional sign shops, Culpeper, Richmond, and Lynchburg. Each sign shop is responsible to supply traffic-control equipment to a number of districts, which in turn supply to a number of residencies. Each residency is responsible for supplying the needs of one to two counties. The Richmond regional sign shop supplies signs to the Suffolk District.

In case of a hurricane, all three regional signs shops would contribute to the recovery of affected area. If the sign shops are unable to meet the demand of signs, signals and lights to substitute the damaged ones, VDOT would then hire a private contractor (Balderson, 1999).

Overview: Use of Forecasting

This section describes two multi-objective decision models for evaluating policies to determine appropriate alternative levels of reserves. Both models incorporate forecasts and historical data in order to determine the impact of long-term and short-term decisions made prior to a hurricane.

The Introduction section explains the motivation for using decision trees and forecasting and gives an overview of the organization of the chapter.

The Technical Background section explains relevant information used to develop the model. The section discusses current inventory practices and production capabilities, a forecasting study, and decision trees.

The Modeling Hurricane Impacts section details how to characterize the potential damage of signs, signals and lights in an area. Then, in turn, it details the factors that will be used in the following sections for the decision trees. The methods of calculating the three factors, pre-hurricane preparation cost, recovery time and recovery costs, are discussed thoroughly.

The Sequential Decision Making By Highway Agency section discusses in detail the sequential decision-making model. This approach adopts a multi-objective decision tree and explains how to apply seasonal forecasts.

The Conclusion section discusses the conclusions from the application of the multi-objective decision tree.

Technical Background

Introduction

In this section, relevant information required for the development of the models is presented. First, actual production and inventory practices in VDOT are described. The second part of this section discusses hurricane forecasts that are currently available to the decision-making model. The last section describes influence diagrams and the components of decision trees.

VDOT Inventory and Production Practices

There are at least three reasons to maintain reserves of traffic signs, signals, and lights:

- Protect against certain and uncertain adverse events and their consequences (such as earthquakes, flooding, and hurricanes).
- Allow economically efficient production and purchase, e.g. production in lots.
- Allow for transportation delays of materials, e.g. the time for materials for the signs, signals, and lights to reach Virginia.

What is an adequate level of reserves? What if a hurricane strikes and VDOT does not have enough reserves to replace damaged signs, signals, and lights? What if VDOT increases the level of reserves in order to have enough reserves to replace damaged signs, signals, and lights in case a Hurricane Category 3 strikes , but no hurricane strikes? What should be VDOT's policies for signs, signals, and lights in terms of reserves prior to hurricane season?

As stated earlier VDOT has three regional sign shops, Culpeper, Richmond, and Lynchburg in order to meet the demands of reserves for the state of Virginia. Each sign shop is responsible for supplying traffic-control equipment to a number of districts, which in turn supply to a number of residencies. Each residency is responsible for supplying the needs of one to two counties. The Richmond regional sign shop supplies signs to the Suffolk District.

VDOT manages reserves for typical demands that have been determined according to the historical needs of each county. VDOT sign shops request materials monthly to produce signs, signals and lights but they fill orders for each district on a quarterly basis (Balderson, 1999).

In order to determine a method to produce and store reserves of highway signs, signals, and lights to prepare for hurricane landfall, several inventory models were examined. The literature included static and dynamic inventory models (Bartman and Beckman, 1992, Beckman and Krelle, 1986, Bemelmass, 1986, Johnson and Montgomery, 1974, Lewis, 1973, and Schroeder, 1993). All of the inventory models reviewed planned for normal inventory demand and supply. One key issue in planning for reserves is being able to determine the demand; yet because hurricanes are very unpredictable, it is hard to assess the demand.

A typical static formulation for managing reserves is as follows:
The fixed demand model adopts the following notation (Schroeder, 1993):

Where:
D = Demand rate (units per year).
S = Cost per order placed, setup cost ($ per order).
C = Unit cost ($ per unit).
i = Interest rate (%).
Q = Lot size (units per lot).
EOQ = Economic Order Quantity (units per lot).

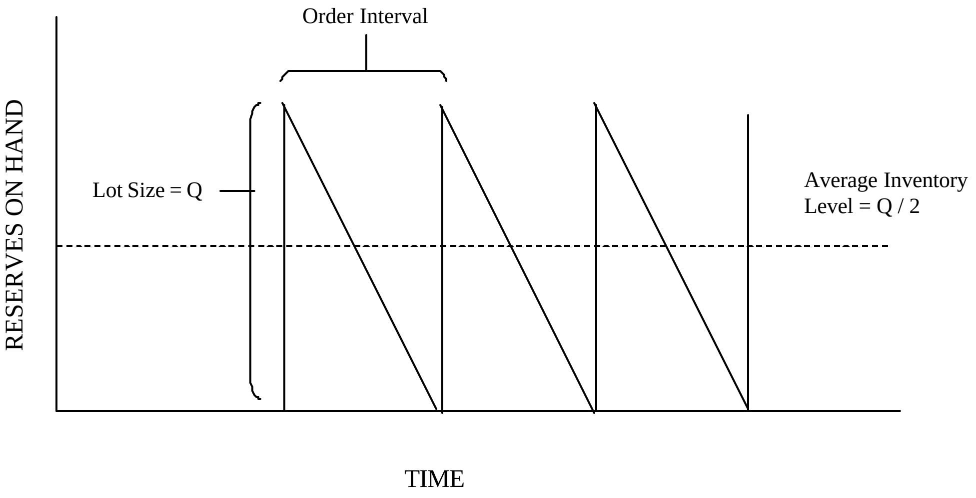

Figure 6.2.1. Economic Order Quantity (EOQ) Inventory Levels (Schroeder, 1993).

As shown in Figure 6.2.1, the average inventory level is the lot size divided by two, which can be expressed by the following equation:

$$Average\ Inventory = \frac{Q}{2} \qquad \text{(units per lot)} \qquad \text{Eq. 6.2.1}$$

Also, the annual ordering cost is the setup cost multiplied by the demand rate, divided by the lot size. The equation is as follows:

$$Ordering \quad Cost \quad per \quad year = S\frac{D}{Q} \qquad \text{(\$/year)} \qquad \text{Eq. 6.2.2}$$

The annual carrying cost is the interest rate multiplied by the unit cost and the lot size divided by two. The equation is as follows:

$$Carrying \quad \cos t \quad per \quad year = \frac{iCQ}{2} \qquad \text{(\$/year)} \qquad \text{Eq. 6.2.3}$$

Total cost per year (TC) is the sum of the ordering cost per year and the carrying cost per year as follows:

$$TC = \frac{SD}{Q} + \frac{iCQ}{2} \qquad \text{(\$/year)} \qquad \text{Eq. 6.2.4}$$

Figure 6.2.2, shown below, details the relationship of total cost, minimum cost, carrying cost, ordering cost, and EOQ.

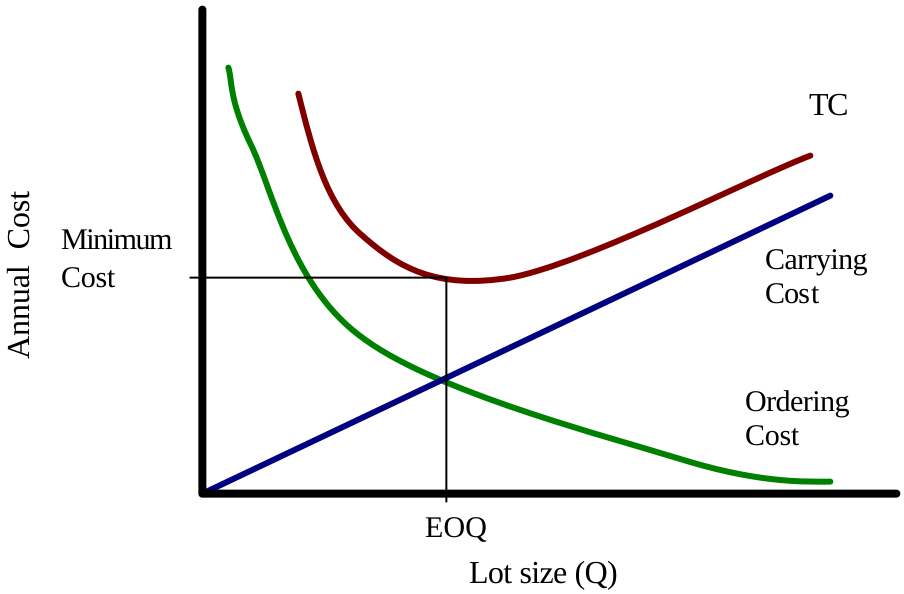

Figure 6.2.2. Lot Size versus Annual Cost. Helps Determine the Minimum Cost and the Economic Order Quantity (EOQ) (Schroeder, 1993)

The EOQ identifies the quantity of the lot size that yields the lowest total cost. Therefore, in order to obtain the lowest cost, the carrying cost has to be set equal to the ordering cost. When both equations are set equal to each other and mathematically manipulated, the carrying cost minus the ordering cost should be equal to zero.

Subsequently, in order to find the value of the lot size (Q) that minimizes total cost (TC), the derivative of total cost is divided by the derivative of the lot size, and the result should equal zero. This is expressed in the following equation:

$$\frac{d(TC)}{d(Q)} = 0 \qquad \text{(\$/units per lot)} \qquad \text{Eq. 6.2.5}$$

Thus, by using the equation of total cost (TC) the following relationship can be obtained:

$$Q = \sqrt{\frac{2SD}{iC}} \qquad \text{(units per lot)} \qquad \text{Eq. 6.2.6}$$

The previous equation states that the lot size is equal to the square root of two times the setup cost times the demand rate divided by the interest rate and the unit cost.

The reorder point is defined as follows:

$R = m + s$ (units per month) Eq. 6.2.7

Where:

R = Reorder point (Time – e.g. month, bimonthly).
m = Average Demand (units per month).
z = Safety factor (%)
σ = Standard deviation of demand over time (units per month).
s = Safety stock. (units per month)

The safety stock is equal to the safety factor times the standard deviation of demand over time. The equation can be expressed as follows:

$s = z\sigma$ (units per month) Eq. 6.2.8

The reorder point refers to the point that when levels of reserves have reached the determined minimum and new equipment orders need to be placed. According to equation (6.2.7), the reorder point is equal to the average demand plus the safety stock.

This model does not account for an unexpected, exorbitant, high demand. One should consider the demand for hurricane season to be probabilistic and not fixed. And one should address the fact that although a higher demand of reserves is required during the hurricane season, because of hurricane unpredictability, the static model for setting levels of reserves described just above does not apply.

Seasonal Hurricane Forecasts

Technology has provided a tool to forecast the intensity of the hurricane season. Several studies have been conducted to determine seasonal hurricane impacts (Elsner, 1998, Marks and Shay, 1997, and Gray and Landsea, 1999). Colorado State University's department of Atmospheric Science has done extensive works on hurricane forecasting. They provide a seasonal forecast that could prove very useful in allowing VDOT officials to make critical decisions prior to and during hurricane season. Seasonal forecasts for the whole United States are conducted in December of the previous year (Gray et al., 1992). Verifications are conducted of the hurricane forecasts before June 1 and before August 1 (Gray et al., 1993 and Gray et al., 1994). The forecasts used are verified by comparing them to historical climatological data (Landsea 1993, Landsea and Gray, 1992a, and Landsea et al., 1992b). Additional forecasts are publicized in April, June, August and November (Gray and Landsea, 1999).

Many factors are considered in forecasting hurricanes. Studies show the relationship of El Niño currents, sea levels, quasi-biennial oscillations, and the Sahel rains to hurricane formation (Gray, 1984a, Knaff, 1997, Landsea and Gray, 1992a, and Landsea et al., 1992b)

The forecasts used in this document are based on ten potential predictors shown in Table 6.2.1 (Gray and Landsea, 1999).

Table 6.2.1. Climatological Predictors Used in Forecasting Seasonal Hurricanes (Gray and Landsea, 1999)

Climatological Predictors
U_{50} :10 month extrapolated 50 mb (mb = atmospheric pressure in millibars) Quasi-Biennial (QBO) zonal wind near 10°N for September of the forecast year.
U_{30}: 10 month extrapolated 30 mb Quasi-Biennial (QBO) zonal wind near 10°N for September of the forecast year (Gray, 1984a).
$\lvert U_{50} - U_{30} \rvert$: 10 month extrapolated 50 mb minus 30 mb QBO absolute value of zonal wind for September of the forecast year.
Guinea Rain (Aug-Nov)
West Sahel rain (Jun-Sep) (Landsea, 1992a and 1992b)
Atlantic Ridge (Oct-Nov)
Darwin (May-Jul)
Niño-4 Trend (Aug-Oct)-(May-Jul) (Goldenburg, 1996)
SOI (Aug-Oct)
SOI Trend (Aug-Oct)-(May-Jul)

Figure 6.2.3 offers a comparison of the August forecasts versus the observed named storms and the long-term climatological mean(Gray and Landsea, 1999).

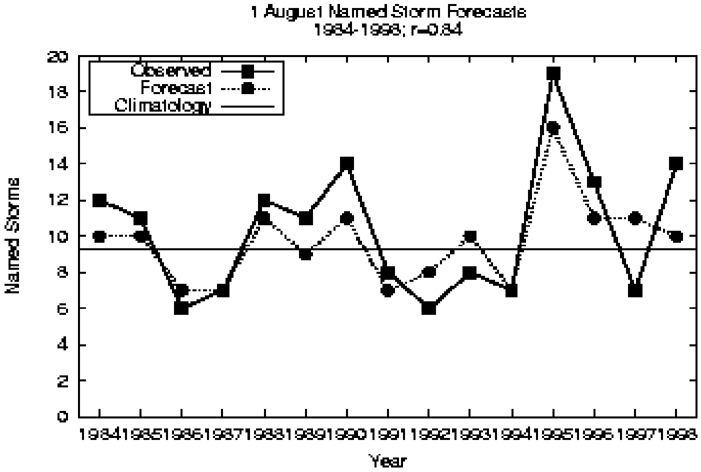

Figure 6.2.3. August Prediction of Total Named Storms Versus the Number of Actually Observed Versus Long-Term Climatological Mean (R = 0.85) for Period 1984-1998 (Gray and Landsea, 1999)

Figure 6.2.4 offers a comparison of the August forecasts versus the observed hurricanes and the long-term climatological mean. (Gray and Landsea, 1999).

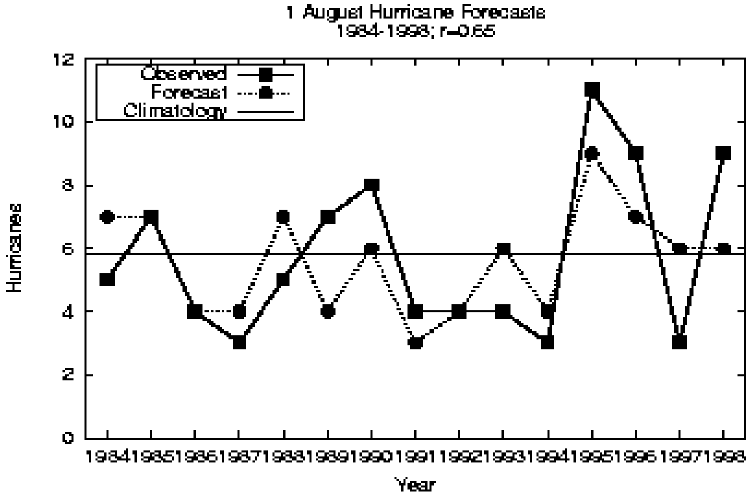

Figure 6.2.4. August Prediction of Total Hurricanes Versus the Number of Actually Observed Versus Long Term Climatological Mean (R = 0.65) For Period 1984-1998 (Gray and Landsea, 1999)

Figures 6.2.3 and 6.2.4 show the accuracy of the forecasts in the last fourteen years. Another important relationship observed in these graphs is the number of hurricanes or storms that are observed compared with the climatological average.

The Colorado State forecast study segments the probabilities of each type of hurricanes per region. As seen in Figure 6.2.5, Virginia is located in Region 9.

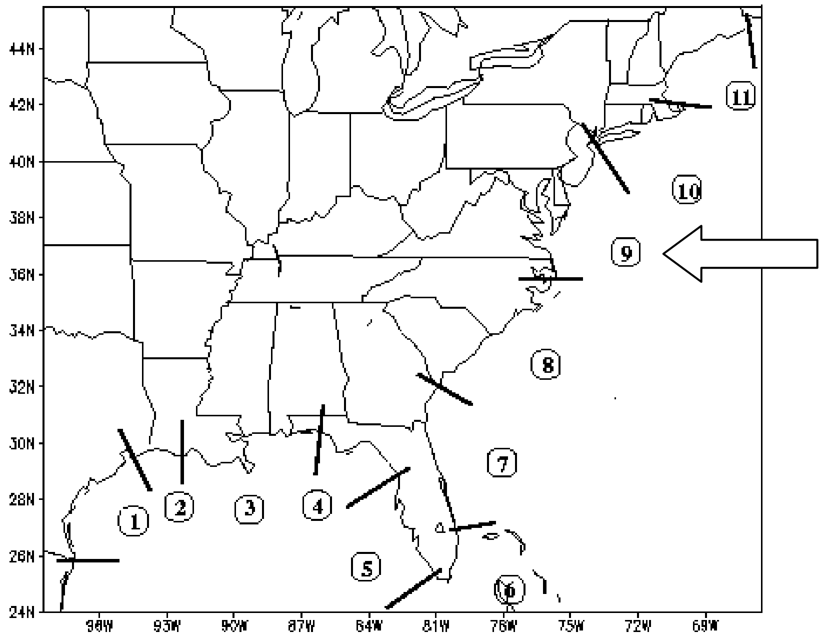

Figure 6.2.5. Location of the 11 Coastal Regions for which Separate Probabilistic hurricane forecasts are Made (Gray and Landsea, 1999)

As specified in Table 6.2.3, separate probabilities of impact are generated for each region. Table 6.2.3 separates the probabilities for TS (tropical storms), minor hurricanes (Category 1-2), and intense hurricanes (Category 3-4-5).

For 1999, the following forecast was issued for the eleven regions detailed in Figure 6.2.5:

Table 6.2.2. Example of Tropical Storm Forecast of 1999 Hurricane Season. (Gray and Landsea, 1999)

Description	No. of Storms
All named storms	14
All hurricanes	9
Intense hurricanes	4

Table 6.2.2 shows how many hurricanes are predicted for the entire US region. Out of fourteen storms predicted, nine are said to be hurricanes. Of those nine hurricanes, four are intense hurricanes, which means that they are category three or higher. Figures 6.2.3 and 6.2.4 illustrate that the climatological mean is 9 named storms and 6 hurricanes. Therefore, one can conclude that the predicted hurricane season is a high hurricane season. In other words the 1999 hurricane season is 185% above normal.

For example, Table 6.2.3 gives a probabilistic hurricane forecast for the 1999 hurricane season for the eleven (11) US regions.

Table 6.2.3. Example of Probability Forecast of 1999 Hurricane Season. (Gray and Landsea, 1999)

Region	TS	Category 1-2	Category 3-4-5
Coastal Region Gulf			
1	22	30	23
2	13	10	4
3	46	29	31
4	20	10	< 2
Florida Plus East Coast			
5	19	7	10
6	15	27	29
7	19	8	< 2
8	28	30	20
9	7	10	< 2
10	5	7	11
11	7	6	< 2

The forecasts of Table 6.2.3 represent the probabilities that one or more TS, H-1-2, or H-3-4-5 will strike each of the specified regions. For example, the table shows that for Region 9 which consists of Virginia, Maryland, and Delaware, there is a 7% probability of one or more tropical storms striking, a 10% probability of a Category 1 or 2 Hurricane striking and a less than 2% probability of a Category 3, 4, or 5 Hurricane striking.

The forecast is also revised and published in April, June, and August. The final verification of the forecast is published in November.

The forecasts can provide the highway agency with a characterization of the type of season to be expected for a given year. The season can be determined as a high or low year for hurricanes.

Influence Diagrams and Decision Trees

The main concerns for VDOT were the decisions concerning reserves of traffic equipment, especially during hurricane season. Different techniques on decision modeling were studied. Golub discusses the importance of defining the problem in order to make good decisions (Golub, 1997). The trade-offs in the results of decision tree will provide VDOT with several policies to adopt prior to hurricane landfall. Keeney and Raiffa (1993) discuss the use of utility theory in order to assess the trade-offs. Yet for the document a different approach was utilized to obtain the different policies. A multi-objective framework approach was exercised to determine the trade-offs (Chankong, V. and Haimes, 1983, Haimes and Li, 1990, Haimes et al., 1990, Haimes, 1998, Kirkwood, 1992, Raiffa, 1968, and Steur, 1986). The "optimal" allocations of the resources are meant in the Pareto optimal sense where trade-offs among costs, losses, time, benefits, and risks are evaluated in terms of hierarchical objectives and their temporal impacts on future options (Haimes, 1998).

Influence Diagrams

Influence diagrams represent a high-level view of a decision analysis problem. The influence diagram shows the relationships between the decision elements. By convention the influence diagram is expressed chronologically from left to right starting with the primary decision.

The components of influence diagrams are (Golub, 1997):

- Decision node: Represented by squares. A decision is defined to be a choice between two or more alternatives.
- Chance node: Represented by circles or ovals. A chance node is also known as an uncertain event, which is a situation outside the control of the decision maker that could result in either of two or more possible outcomes.
- Consequence node: Represented by a diamond. The consequence also known as an outcome or attribute, is the different payoff from each path through the influence diagram. There can be multiple dimensions (e.g., costs, times, losses) to payoff; thus it is designated as a multi-objective diagram.
- Relationships: Arrows represent the relationships between the decision elements. The direction of the influence arrow indicates the direction of influence from the decision to the uncertain event.

Figure 6.2.6 is an illustration of an influence diagram:

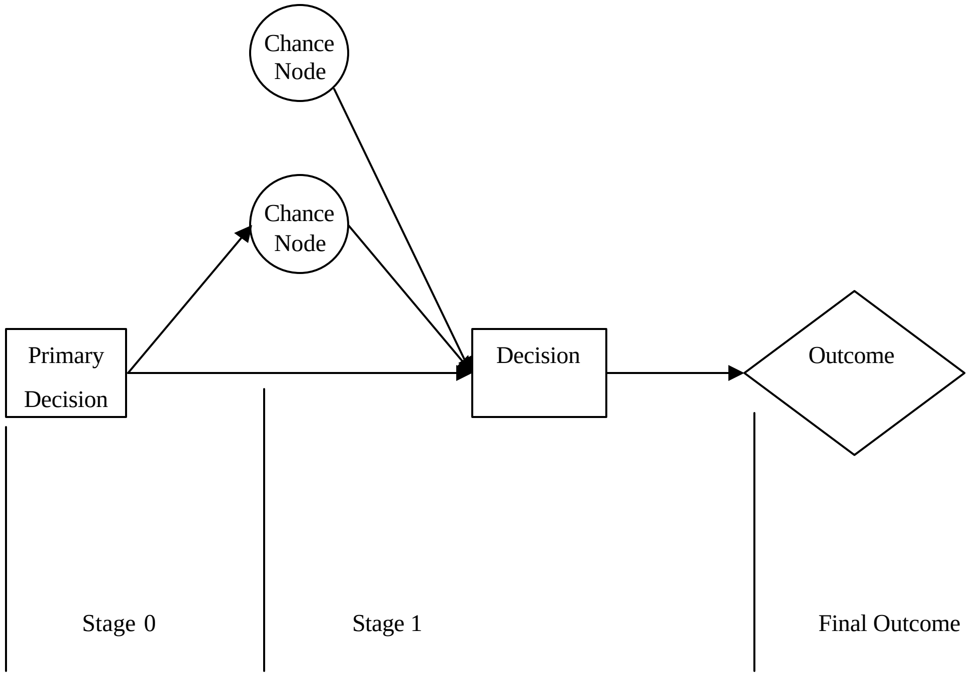

Figure 6.2.6. Illustration of the Different Components of an Influence Diagram. (Golub, 1997)

From the influence diagram one can derive a decision tree.

Decision Trees

Decision trees are one of the most commonly used tools in risk-based decision-making (Haimes, 1998). Decision tree diagrams are tools that provide a clear analysis through graphical representation of how current decisions impact future options.

Decision trees are formed by the following components:

- Decision Node. Decision nodes are represented by a square. The branches that part from this node represent the multiple alternatives available to the decision-maker.
- Chance Node. A circle represents chance nodes. The branches that part from this node represent the possible states of nature. Each branch has a probability assigned to it.
- Consequences. Consequences, also known as outcomes or attributes, are the different payoffs from each path through the decision tree. There can be multiple dimensions (e.g., costs, times, losses) to payoff, thus it is designated as a multi-objective tree.

Figure 6.2.7 is an illustration of a decision tree:

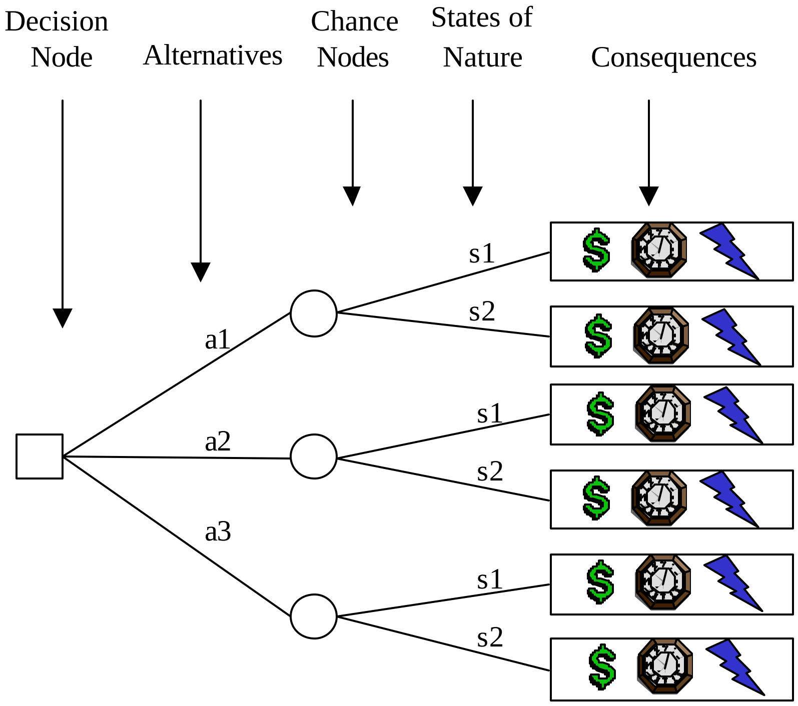

Figure 6.2.7. Illustration of the Different Components of a Decision Tree (Haimes, 1998)

Modeling Hurricane Impacts

Introduction

In this section, two critical issues that are required to support the multi-objective decision trees are established. The first is to establish the amount of traffic-control equipment that experiences hurricane winds in the Suffolk region; or in other words, the expected value of percentage of hurricane damage to signs, signals and lights. The second factor is to determine the attributes to be used in the decision tree, which are pre-hurricane preparation cost, recovery time and recovery cost in case of a hurricane.

Potential Damage

There are different categories of hurricanes (I, II, III, IV, and V) that have unique maximum sustained wind speeds. The circular motion of a hurricane creates different levels of wind speeds throughout an area. Also, each category of hurricane usually has a different path of destruction (diameter). Therefore, there are different normal density functions for hurricanes of each category. Each of these functions has a mean and standard deviation that defines the normal distribution.

The point estimate of maximum wind speed was inadequate across a wide region for use in impact analysis. Therefore, the characterization of maximum wind speed across a region was determined by the following:

The Saffir-Simpson scale detailed in Table 6.3.1 provides a description of wind behavior for each category of hurricanes. The distribution is assumed to be normal, like the one seen in Figure 6.3.1. The lower tail, 5%, is roughly the same for all categories of hurricanes. The assumption used is that the region will experience wind speeds less than or equal to 5-mph winds. The upper tail of the distribution is determined by the highest wind speed specified for each of the categories in the Saffir-Simpson scale. The assumption used is that the region will experience wind speeds 10% greater or equal than the highest wind speed specified in the Saffir-Simpson scale. So, for example, for a Hurricane Category 3 the region would experience wind speeds 10% greater or equal to 130-mph.

In order to calculate the mean and the standard deviation, the values for two percentiles are used. The percentiles chosen were the 5th and 90th. The 5th percentile is the wind speed for which 5% of the installed equipment experience less than that speed. According to the assumptions, the 90th percentile is the maximum sustained wind speed of a hurricane and the 5th percentile is 5 miles per hour. Figure 6.3.1 illustrates the 5th percentile and the 90th percentile.

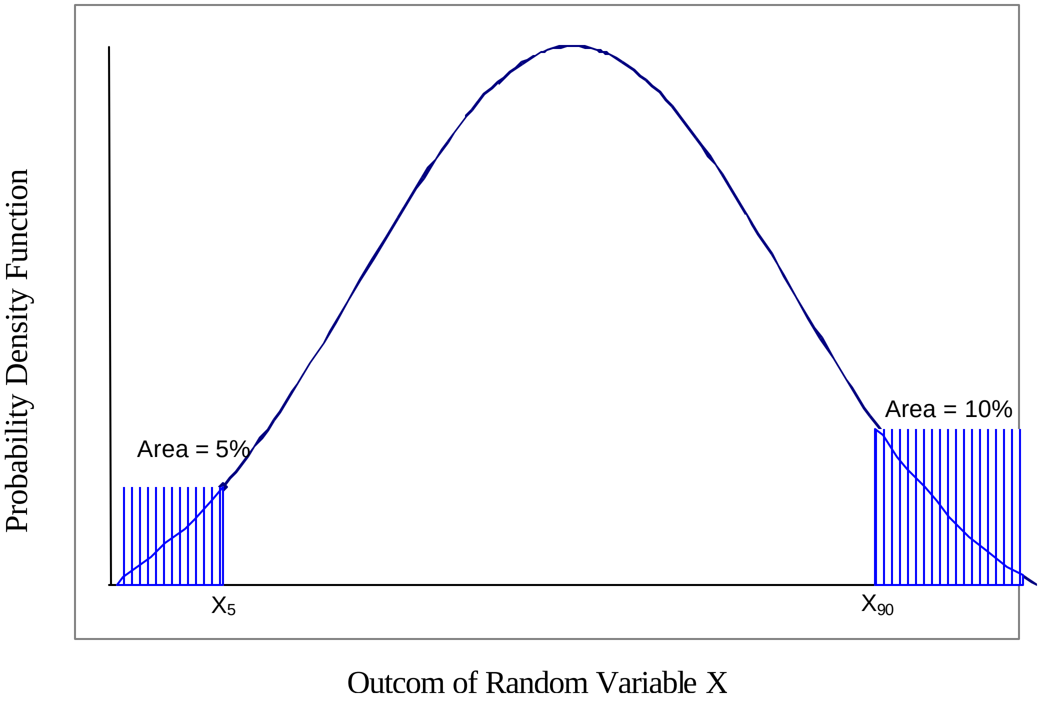

Figure 6.3.1. Curve Illustrating 5th Percentile (X_5) and the 90th Percentile (X_{90})

The following are the calculations for the mean (μ) and standard deviation (σ) (Capstone 98-99, 1999).

The following notation will be used in the calculations:

μ = Mean (mph).

σ = Standard deviation (mph).

X_5 = 5th percentile (mph).

X_{90} = 90th percentile (mph).

Φ = Standard normal cumulative distribution function (CDF)

First, normalize the 5th percentile, or X_5, by subtracting the mean from it and dividing by the standard deviation. Since it is the 5th percentile, the probability that a piece of equipment selected at random will experience winds with speeds of at most X_5 is 0.05.

Therefore,

$$\Phi\left[\frac{(X_5 - m)}{s}\right] = 0.05 \qquad \text{Eq. 6.3.1}$$

Solving for the mean in equation 3.1 results in the following expression:

$$m = X_5 - \left[\Phi^{-1}(0.05)\right]s \qquad \text{Eq. 6.3.2}$$

Similar to $X_{5,}$ the following expression represents the 90th percentile.

$$\Phi\left[\frac{(X_{90} - m)}{s}\right] = 0.90 \qquad \text{Eq. 6.3.3}$$

Solving for the standard deviation in equation 6.3.3 results in the following:

$$s = \frac{(X_{90} - m)}{\Phi^{-1}(0.90)} \qquad \text{Eq. 6.3.4}$$

Substituting the expression σ of equation (6.6.3.4) into equation (6.6.3.2) yields:

$$m = X_5 - \left[\Phi^{-1}(0.05)\right]\frac{(X_{90} - m)}{\Phi^{-1}(0.90)} \qquad \text{Eq. 6.3.5}$$

Solve for μ by conducting algebraic calculations (multiply and divide). Solving for μ yields:

$$m = X_5 - \frac{\Phi^{-1}(0.05)X_{90}}{\Phi^{-1}(0.90)} + \frac{\Phi^{-1}(0.05)m}{\Phi^{-1}(0.90)} \qquad \text{Eq. 6.3.6}$$

Simplifying equation (6.3.6) yields:

$$\left[1 - \frac{\Phi^{-1}(0.05)}{\Phi^{-1}(0.90)}\right]m = X_5 - \frac{\Phi^{-1}(0.05)X_{90}}{\Phi^{-1}(0.90)} \qquad \text{Eq. 6.3.7}$$

For clarity, let:

$$a = \frac{\Phi^{-1}(0.05)}{\Phi^{-1}(0.90)} \qquad \text{Eq. 6.3.8}$$

Then the final results for the μ of the distribution can be expressed as follows:

$$m = \frac{(X_5 - aX_{90})}{(1 - a)} \qquad \text{Eq. 6.3.9}$$

Therefore, substituting the expression for μ into equation (6.6.3.4), yields the equation for the standard deviation of the distribution, which is as follows:

$$s = \frac{\left(X_{90} - \frac{(X_5 - aX_{90})}{(1-a)} \right)}{\Phi^{-1}(0.90)} \qquad \text{Eq. 6.3.10}$$

The highest maximum sustained wind speed of each hurricane category was used as the 90th percentile. Table 6.3.1 shows the maximum sustained wind speeds for each category of hurricane. By taking the highest maximum sustained wind speed for each category as the 90th percentile, the worst-case scenario is being considered and the expected damage calculated from the model is the greatest one could expect.

Table 6.3.1. Saffir-Simpson Scale, Hurricane Wind Speed by Category (Cole, 1998).

Category	Maximum Sustained Wind Speed (mph)
TS	39-74
I	74-95
II	96-110
III	111-130
IV	131-155
V	156+

The 5th and 90th percentiles for each category of hurricane are in Table 6.3.2. (Capstone 98-99, 1999).

Table 6.3.2. Hurricane Scenario Definitions.

		Value (miles per hour)					
Percentile	%	TS	I	II	III	IV	V
Upper	90	74	95	110	130	155	176
Lower	5	5	5	5	5	5	5

Notice that for Hurricane Category 5, a wind speed of 176 mph had to be assumed due to the fact that there is no limit in this category. However hurricanes such as Hurricane Mitch (Category 5) that struck Central America in 1998 reached wind speeds of 188 mph.

The values for the mean and standard deviation for each hurricane category were calculated using equation 6.3.8, equation 6.3.9 and equation 6.3.10. The values obtained can be seen in Table 6.3.3.

Solve for a in Equation (6.3.8):

$$a = \frac{\Phi^{-1}(0.05)}{\Phi^{-1}(0.90)} = \frac{-1.645}{1.282} = -1.283$$

To solve for μ substitute the values from Table 6.3.2 and the value of "a" into equation (6.3.9), so for hurricane category 1 μ =:

$$m = \frac{(X_5 - aX_{90})}{(1-a)} = \frac{(5-(-1.283)(95))}{(1-(-1.283))} = 56$$

To solve for σ substitute the values from Table 6.3.2 and the value of "a" into equation (6.3.10), so for hurricane category 1 σ =:

$$s \ = \frac{\left(X_{90} - \dfrac{(X_5 - aX_{90})}{(1-a)}\right)}{\Phi^{-1}(0.90)} = \frac{\left(95 - \dfrac{(5-(-1.283)(95))}{(1-(-1.283))}\right)}{1.282} = 31$$

The same calculations are performed for all types of storms.

Table 6.3.3. Mean and Standard Deviation for the Normal Distribution of each Hurricane Category

Parameters	Values (miles per hour)					
	TS	I	II	III	IV	V
μ	44	56	64	75	89	101
σ	24	31	36	43	51	58

Once the density function was found for each hurricane category, the expected equipment damage can be calculated.

Figure 6.3.2 shows the density functions for tropical storms and the five hurricane categories. Along the horizontal axis are the maximum sustained wind speeds that can be experienced during a hurricane. The vertical axis is the probability density.

For each hurricane category, there is a range of wind speeds to account for the fact that not every piece of traffic-control equipment experiences the same wind speed. Each type of sign, signal and light is designed to experience different levels of sustained winds. In Table 6.3.4 is a description of what maximum sustained wind speeds each general type of traffic-control equipment may endure.

Table 6.3.4. Ultimate Wind Velocities of Traffic Equipment (VDOT, 1997)

Damageable Equipment	Ultimate Wind Velocities (miles per hour)
Shoulder-mounted signs	86
Cantilever signs	117
Two pole span signs	121
Traffic signals systems	99
High mast lighting structures	111
Roadway lighting structures	99

Another factor that affects how easily equipment is damaged is its age and condition. Also, signs experience different shielding from high winds or are oriented differently (some facing the south, others the west). One can use the functions in Figure 6.3.2 to calculate expected fraction of equipment damage.

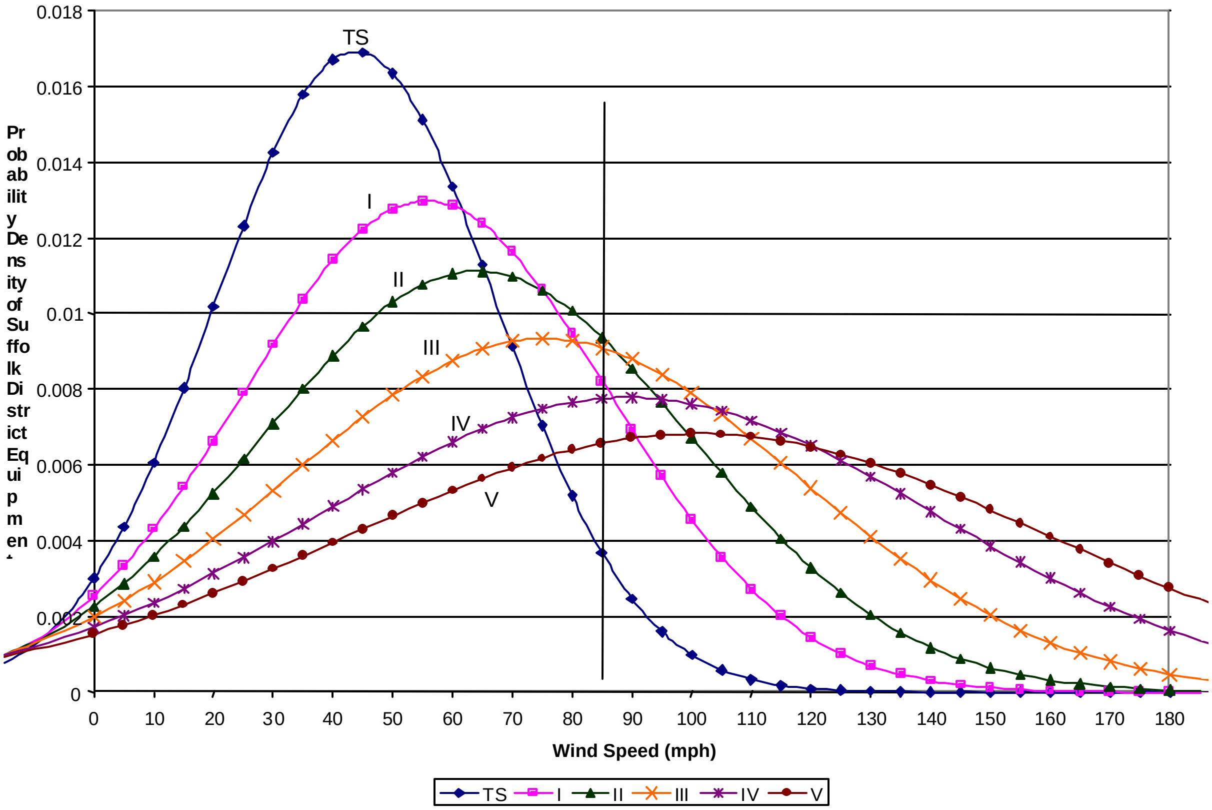

Figure 6.3.2. Probability Density Functions of Wind Speed for the Five Hurricane Categories and Tropical Storms

In order to calculate the fraction of damaged signs, signals, or lights the following calculations have to be computed:

The probability density for a normal distribution is as follows:

$$i = I, II, III, IV, V$$

$$p(x) = \frac{1}{\sqrt{2\pi\sigma_i^2}} \exp\left(\frac{-(x-\mu_i)^2}{2\sigma_i^2}\right) \qquad \text{Eq. 6.3.11}$$

The fraction of signs damaged (f) can be explained by the following equation:

Let β = wind speed design standard (mph).

$$f = \int_{\beta}^{\infty} p(x)dx \qquad \text{Eq. 6.3.12}$$

From Table 6.3.4, ground-mounted signs can withstand sustained winds of 86 mph. The 86 mph is considered to be the parameter β. Therefore, the equation has to be evaluated between 86 mph and infinity, where the area under the curve is the percentage of signs that would experience sustained wind speeds greater than 86mph. The number obtained from the calculation is the percentage of ground-mounted signs damaged for each type of storm.

Example:

From Table 6.3.3 the following information is provided for a Hurricane Category 5:

Parameters	Values (miles per hour)
	V
μ	101
σ	58

Ground-mounted signs withstand a maximum of 86 miles per hour, so β = 86 miles per hour.

Therefore the normal distribution for a Hurricane Category 5 using the values from Table 6.3.3 and substituting them into equation 6.3.11 is the following:

$$p(x) = \frac{1}{\sqrt{2p\,(58)^2}} \exp\left(\frac{-(x-101)^2}{2(58)^2} \right)$$

Then evaluate the function accordingly using equation 6.3.12:

$$f = \int_b^\infty p(x)dx$$

$$f = \int_{86}^\infty \frac{1}{\sqrt{2p\,(58)^2}} \exp\left(\frac{-(x-101)^2}{2(58)^2} \right) dx = 0.60$$

Table 6.3.5 shows the calculations for the percentage damaged of ground-mounted signs that can withstand 86 mph winds obtained by using the mean and standard deviations given in Table 6.3.3 for each type of hurricane.

Table 6.3.5. Percentage of Damage to Ground-mounted Signs Design, Standard of 86 Mph., for every Category of Hurricane (%)

Situation	% of Damage (D)
None	0%
TS	5%
Hurricane 1	16%
Hurricane 2	27%
Hurricane 3	40%
Hurricane 4	53%
Hurricane 5	60%

For the calculations in the tree, only the values from Table 6.3.6 are used, always taking the worst case scenario.

Table 6.3.6. Percentage of Damage to Ground-mounted Signs for each Classification of Hurricane

Situation	% of Damage (D)
None	0%
TS	5%
Hurricane 1-2	27%
Hurricane 3-4-5	60%

The percentage for each classification of hurricane was obtained from the worst possible case of storm within each classification. Damage depends considerably on wind speed, but also on storm surge and rain. The strength of storm surge or how wet a hurricane will be is very hard to determine or predict. The higher the surge and the higher the rainfall, the greater the damage.

Decision Tree Attributes

There are three attributes that will be considered in each of the models: pre-hurricane preparation cost, recovery time, and recovery cost. Each of the attributes has a different calculation which will be described in the two following sections.

In order to calculate the recovery time and the recovery cost a flow diagram is used. The flow diagram method used describes the cost and amount of time that it would take to install, contract, and produce highway signs, signals and lights.

The third attribute, pre-hurricane preparation cost, relates directly to the decision process. The pre-hurricane preparation cost reflects the cost of the first and second stage decisions of the decision tree described in the Sequential Decision Making By Highway Agency section.

Recovery Time and Recovery Cost

In order to begin to understand recovery time, an analysis of the stages of recovery have to be examined. Recovery has several phases after a hurricane hits. VDOT has the following three options:

- Install signs, signals and lights from the reserves on hand.
- Produce more signs.
- Contract signs, signals, and lights.

From these three options the diagram can be designed. The sequences of events are as follows:

Table 6.3.6. Diagram Tasks and Predecessors for Hurricane Recovery.

Node	Name of Task	Predecessor
A	Hurricane hits (Start)	None
B	Install signs on-hand	A
C	Produce new signs	A
D	Install new produced signs	C
E	Contract new signs	A
F	Install signs made by contractors	E
G	Full Recovery Achieved (End)	B, D, F

From the information in Table 6.3.6 the Figure 6.3.3 can be obtained:

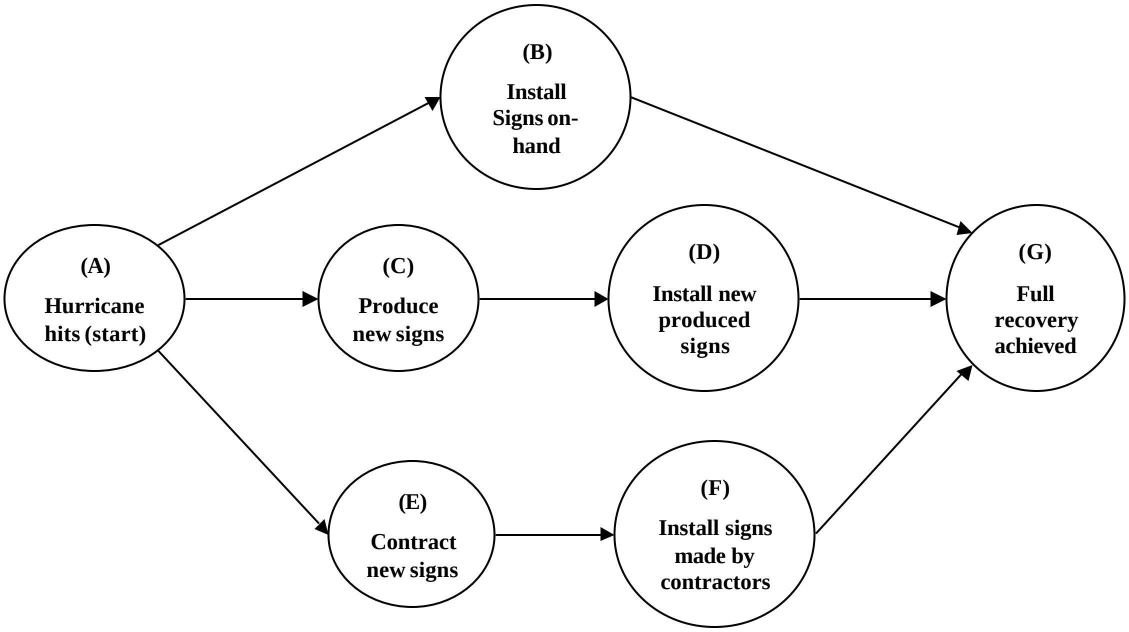

Figure 6.3.3. Diagram of Hurricane Recovery Procedures for Repairing Damaged Highway Signs, Signals and Lights.

The flow to each of the paths can be found as the percentage of signs assigned. VDOT can determine what amount is contracted and the percent that is to be produced in-house. E.g. Contractors would produce 70% of the new signs, while VDOT would produce 30% of the signs. The process is explained in Figure 6.3.4.

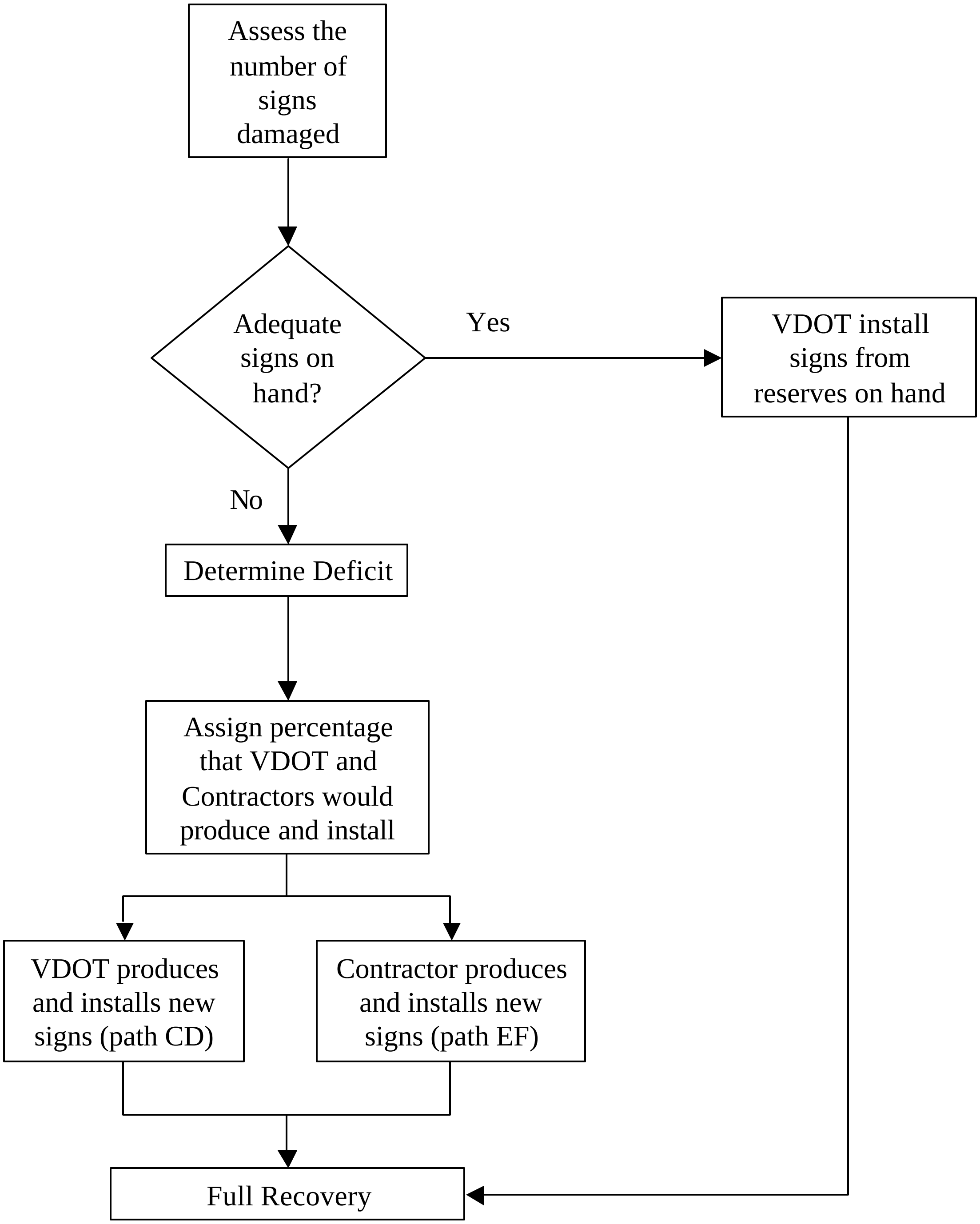

Figure 6.3.4. Flow Diagram of Production and Installation of Damaged Highway Signs, Signals and Lights

Next, the cost and rates of production and installation were determined by the data provided by traffic engineers of VDOT, Korman sign shop, and PIMS report.

The Richmond regional sign shop is capable of producing 175 to 450 signs per day. Four hundred and fifty signs that are 30”x30” can be produced in an eight hour day, yet only 175 signs that are 48”x48” can be produced in a day (Bridewell, 1999a).

Contractors can produce from 600 to 800 30”x30” signs per day and 400 to 500 48”x48” signs per day (Alexander, 1999). Usually contractors don’t conduct the installation but if they did they could install 30 to 50 signs per day depending on authorization required by “Miss Utility”. “Miss Utility” maintains a database of buried pipes and utilities in order to prevent damages to these utilities due to construction of new structures, including highway sign, signals, and lights. “Miss Utility” takes about 48 hours to authorize 30 to 50 signs.

In an emergency, VDOT has the authorization to replace signs without going through “Miss Utility”. If new signs need to be installed, an emergency authorization is required, which would take less than three hours to be approved. VDOT’s installation capabilities depend on the availability of crews. Each crew is able to install seven to eight signs per day or even up to 12 signs per day. At the present time, the Richmond VDOT sign shop is only equipped with two installation crews (Bell and Lamb, 1999).

Assume that there are12,100 shoulder-mounted signs in the Suffolk District, estimated roughly by considering that there are 50 signs per interchange and 40 per road mile of divided highway, and that there are 212 intersections (Bridewell, 1998) and 37.5 miles of divided highway. The data collected is shown in Tables 6.3.7 and 6.3.8 (Capstone 98-99, 1999).

Table 6.3.7. Average Densities of Signs, Signals and Signs in Virginia (Bridewell, 1998)

<table>
<tr><th>Item</th><th colspan="2">Average Density</th></tr>
<tr><td>Lights</td><td colspan="2">38 per mile of road</td></tr>
<tr><td>Two-pole Span Signs</td><td colspan="2">2 per interchange</td></tr>
<tr><td>Cantilever Signs</td><td colspan="2">4 per interchange</td></tr>
<tr><td rowspan="5">Ground-mounted Signs</td><td colspan="2">50 per full interchange</td></tr>
<tr><td>Rural</td><td>Urban</td></tr>
<tr><td>15 per intersection</td><td>20 per intersection</td></tr>
<tr><td>20 per Road Mile (undivided)</td><td>30 per Road Mile (undivided)</td></tr>
<tr><td>25 per Road Mile (divided)</td><td>40 per Road Mile (divided)</td></tr>
</table>

Table 6.3.8. Number of Signs by Type in Suffolk District

Equipment Type	Amount Installed in Suffolk District	Source of Data
Ground-mounted Signs	12100	Density from Table 6.3.7
Cantilever Signs	320	Roney (1999)
Two pole span Signs	335	Roney (1999)
Traffic Signal Systems	200	Pauley (1999)
High-Mast Lights	260	Meredith (1999)
Roadway Lights	4940	Density from Table 6.3.7

For the analysis, the following were assumed for ground-mounted signs 30”x30”:

- The average cost of a shoulder-mounted sign made by VDOT = $80.
- The average cost of a shoulder-mounted sign made by a contractor = $180.
- Actual storage capacity of VDOT is 300-500 signs.

The most critical types of signs required after a hurricane include emergency signs, stop signs, arrows, and detour signs (Bridewell, 1999b).

In general, contractors charge twice or three times as much as VDOT’s cost of producing signs, signals and lights. Recent experience with floods near Culpeper proved to VDOT that contracting was more expensive (Balderson, 1999).

The data and assumptions that have to be taken into consideration are summarized in Table 6.3.9.

Table 6.3.9. Summary of Data and Assumptions Used in the Calculations for the Recovery time and Recovery cost for Ground-mounted Signs 30”X 30”

Size of Sign	30" x 30"			
Number of a type Sign, Signal, or Light in Suffolk =	12100	signs		
Number of signs on hand	1000	signs		
Contracting Cost of these types of signs ($) =	180.00			
Cost for VDOT to make sign ($) =	80.00			
Percentage allocated for Contractor to Produce	70%			
Percentage allocated for VDOT to Produce	30%			
Rate of installation of signs (Contractor)	0.0286	days/sign	35	signs/day
Rate of installation of signs (VDOT)	0.0417	days/sign	12	signs/day
Rate of Production for Contractor	0.0014	days/sign	700	signs/day
Rate of Production for VDOT	0.0050	days/sign	200	signs/day
Number of Crews (VDOT)	2			
Labor days in a week	5	days		

Due to the nature of the diagram illustrated in Figure 6.3.3, nodes C and D can be added together to form one node called "Production and Installation of Signs by VDOT". E and F can be also added together to form one node called "Production and Installation of Signs by Contractor". Figure 6.3.5 illustrates the summarized diagram of a hurricane recovery procedure.

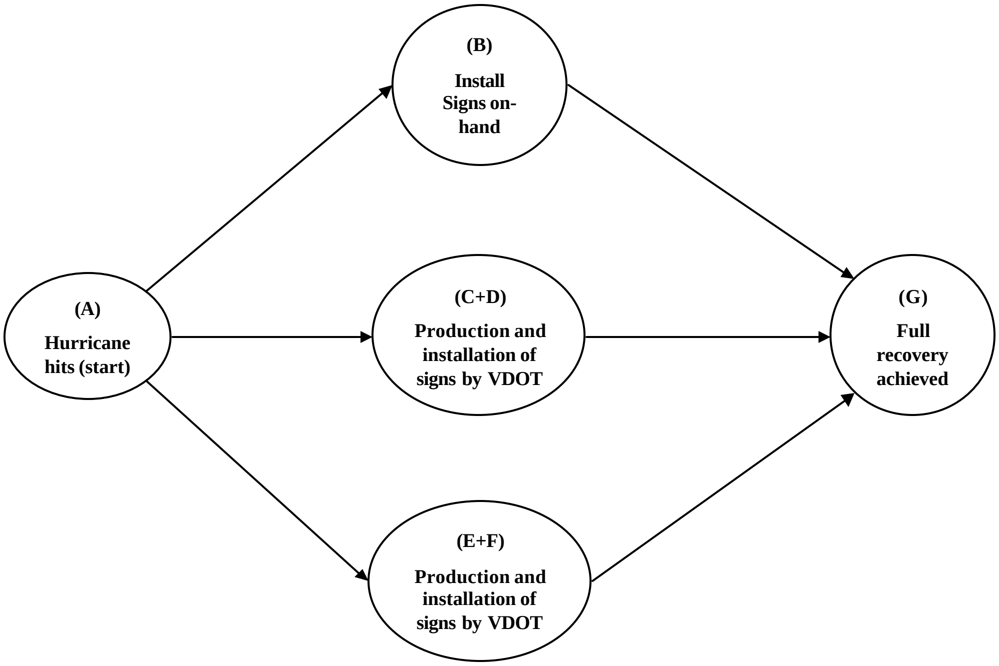

Figure 6.3.5. Simplified Diagram of Hurricane Recovery Procedures for Repairing Damaged Highway Signs, Signals and Lights.

The objective of the diagram illustrated in Figure 6.3.3 is to find the maximum time and cost to achieve full sign recovery after a hurricane strikes. The following equations apply in order to find the maximum time and cost to achieve recovery.

It is assumed if the quantity on hand is less than or equal to the number of damaged signs, then the reserves used are the ones on-hand and none have to be manufactured.

Using Figure 6.3.3 and Figure 6.3.4, the following calculations can be done to derive the recovery time and recovery cost.

Notation:

S = Total number of signs installed in the region (signs).
D = Percentage of damage that a storm can cause (values come from Table 6.3.6) (%).
A = Actual number of signs on hand in VDOT (signs).
N = Potential number of signs damaged (signs).
P_V = Percentage of new signs assigned to be produced and installed by VDOT in case of a hurricane (%).
P_C = Percentage of new signs assigned to be produced and installed by a contractor in case of a hurricane (%).
D = Number of labor days in a week (days/week).

I_V = Installation rate for VDOT (days/sign).
I_C = Installation rate for a contractor (days/sign).
R_V = Production rate for VDOT (days/sign).
R_C = Production rate for a contractor (days/sign).
C_V = Cost of production and installation for VDOT ($).
C_C = Cost of production and installation for a contractor ($).
T_B = Recovery time for node B, install signs on-hand (days).
T_{CD} = Recovery time for path CD, VDOT installing and producing new signs (days).
T_{EF} = Recovery time for path EF, contractors installing and producing new signs (days).
C_B = Recovery cost for node B, install signs on-hand ($).
C_{CD} = Recovery cost for path CD, VDOT installing and producing new signs ($).
C_{EF} = Recovery cost for path EF, contractors installing and producing new signs ($).
E_T = Expected recovery time (weeks)
E_C = Expected recovery cost ($)

First the potential number of signs damaged (N) has to be calculated. The potential number of signs damaged (N) is equal to the total number of signs installed in a region (S) times the percentage of damage (D). The equation can be expressed as follows:

$$N = S * D \qquad \text{(Signs)} \qquad \text{Eq. 6.3.13}$$

Node B, installing signs on-hand, adheres to the following rules:
If the potential number of signs damaged is less than or equal to the actual number of signs on hand in VDOT ($N \le A$) then:

The recovery time for node B is equal to the potential number of signs damaged times the installation rate at VDOT divided by the number of labor days in a week.

$$T_B = \frac{N * I_V}{D} \qquad \text{(Weeks)} \qquad \text{Eq. 6.3.14}$$

The recovery cost for node B is equal to the potential number of signs damaged times the cost of production and installation for VDOT.

$$C_B = N * C_V \qquad (\$) \qquad \text{Eq. 6.3.15}$$

Else:

The recovery time for node B is equal to the actual number of signs on hand in VDOT times the installation rate for VDOT divided by the number of labor days in a week.

$$T_B = \frac{A * I_V}{D} \qquad \text{(Weeks)} \qquad \text{Eq. 6.3.16}$$

The recovery cost for node B is equal to the number of signs on hand in VDOT times the cost of installation for VDOT.

$$C_B = A * C_V \qquad (\$) \qquad \text{Eq. 6.3.17}$$

Path CD, VDOT installing and producing new signs, adheres to the following rules:
If the potential number of signs damaged is less than the actual number of signs on hand (N ≤ A) then:

The recovery time for path CD, for VDOT producing and installing new signs, is equal to zero.

$$T_{CD} = 0 \qquad \text{(Weeks)} \qquad \text{Eq. 6.3.18}$$

The recovery cost for path CD, for VDOT producing and installing new signs, is equal to zero.

$$C_{CD} = 0 \qquad (\$) \qquad \text{Eq. 6.3.19}$$

Else:

The recovery time for path CD, for VDOT producing and installing new signs, is equal to the percentage assigned for VDOT to produce new signs multiplied by the difference of the actual number of signs on hand and the potential number of signs damaged. The result is then multiplied by the summation of the production and installation rates for VDOT divided by the number of labor days.

$$T_{CD} = \frac{(P_V * (N - A)) * (R_V + I_V)}{D} \qquad \text{(Weeks)} \qquad \text{Eq. 6.3.20}$$

The recovery cost for path CD, for VDOT producing and installing new signs, is equal to the percentage assigned for VDOT to produce new signs multiplied by the difference of the actual number of signs on hand and the potential number of signs damaged. The result is multiplied by the cost of production and installation for VDOT .

$$C_{CD} = (P_V * (N - A)) * C_V \qquad (\$) \qquad \text{Eq. 6.3.21}$$

Path EF, contractors installing and producing new signs, adheres to the following rules:
If the potential number of signs damaged is less than the actual number of signs on hand N ≤ A then:

The recovery time for path EF, contractors produce and install new signs is equal to zero.

$$T_{EF} = 0 \qquad \text{(Weeks)} \qquad \text{Eq. 6.3.22}$$

The recovery cost for path EF, contractors produce and install new signs is equal to zero.

$$C_{EF} = 0 \qquad (\$) \qquad \text{Eq. 6.3.23}$$

Else:

The recovery time for path EF, contractors produce and install new signs is equal to the percentage assigned for contractors to produce new signs multiplied by the difference of the actual number of signs on hand and the potential number of signs damaged. The result is multiplied by the summation of the production and installation rates for contractors divided by the number of labor days.

$$T_{EF} = \frac{(P_C * (N - A)) * (R_C + I_C)}{D} \qquad \text{(Weeks)} \qquad \text{Eq. 6.3.24}$$

The recovery cost for path EF, contractors produce and install new signs is equal to the percentage assigned for contractors to produce new signs multiplied by the difference of the actual number of signs on hand and the potential number of signs damaged. The result is multiplied by the cost of production and installation for contractors.

$$C_{EF} = (P_C * (N - A)) * C_C \qquad (\$) \qquad \text{Eq. 6.3.25}$$

To attain the expected recovery time and the recovery cost the following calculations are executed:

To attain the expected recovery time, select the maximum value from the recovery time at node B, CD and EF. The district will not be fully recovered until all tasks are completed this is why the maximum recovery time all three paths is selected.

$$E_T = \max(T_B, T_{CD}, T_{EF}) \qquad \text{(Weeks)} \qquad \text{Eq. 6.3.26}$$

To attain the expected recovery cost, add the values of recovery cost at node B, CD and EF. The costs of all paths are added because the total amount that is incurred by VDOT and paid to the contractors is the total recovery cost.

$$E_C = C_B + C_{CD} + C_{EF} \qquad (\$) \qquad \text{Eq. 6.3.27}$$

An exercise was conducted from the data about production and installation of 30” x 30” ground-mounted signs for VDOT and contractors in Table 6.3.9, which generates the data in Table 6.3.10. The data in table 6.3.10 was used to obtain the recovery time and the recovery cost for several number of signs damaged.The exercise helps to understand the relationships between the number of signs damaged , recovery time, and recovery cost.

Table 6.3.10. Sample Data for Recovery time and Recovery cost Obtained from the Calculations Derived from Figure 6.3.3.

Number of Signs damaged	Time to Install Signs on Hand (B) (weeks)	Time to Produce and Install Signs (VDOT) (C+D) (weeks)	Time to Produce and Install Signs Contractor (E+F) (weeks)	Cost to Install Signs on Hand (B) ($)	Cost to Produce and Install Signs (VDOT) (C+D) ($)	Cost to Produce and Install Signs Contractor (E+F) ($)	Expected Time Recovery (weeks)	Expected Cost of Recovery ($)
0	0.00	0.00	0.00	0	0	0	0.00	0
100	0.83	0.00	0.00	8,000	0	0	0.83	8,000
200	1.67	0.00	0.00	16,000	0	0	1.67	16,000
300	2.50	0.00	0.00	24,000	0	0	2.50	24,000
400	3.33	0.00	0.00	32,000	0	0	3.33	32,000
500	4.17	0.00	0.00	40,000	0	0	4.17	40,000
600	5.00	0.00	0.00	48,000	0	0	5.00	48,000
700	5.83	0.00	0.00	56,000	0	0	5.83	56,000
800	6.67	0.00	0.00	64,000	0	0	6.67	64,000
900	7.50	0.00	0.00	72,000	0	0	7.50	72,000
1000	8.33	0.00	0.00	80,000	0	0	8.33	80,000
1100	8.33	0.28	0.42	80,000	2,400	5,400	8.33	87,800
1200	8.33	0.56	0.84	80,000	4,800	10,800	8.33	95,600
1300	8.33	0.84	1.26	80,000	7,200	16,200	8.33	103,400
1400	8.33	1.12	1.68	80,000	9,600	21,600	8.33	111,200
1500	8.33	1.40	2.10	80,000	12,000	27,000	8.33	119,000
1600	8.33	1.68	2.52	80,000	14,400	32,400	8.33	126,800
1700	8.33	1.96	2.94	80,000	16,800	37,800	8.33	134,600
1800	8.33	2.24	3.36	80,000	19,200	43,200	8.33	142,400
1900	8.33	2.52	3.78	80,000	21,600	48,600	8.33	150,200
2000	8.33	2.80	4.20	80,000	24,000	54,000	8.33	158,000
2100	8.33	3.08	4.62	80,000	26,400	59,400	8.33	165,800
2200	8.33	3.36	5.04	80,000	28,800	64,800	8.33	173,600
2300	8.33	3.64	5.46	80,000	31,200	70,200	8.33	181,400
2400	8.33	3.92	5.88	80,000	33,600	75,600	8.33	189,200
2500	8.33	4.20	6.30	80,000	36,000	81,000	8.33	197,000
2600	8.33	4.48	6.72	80,000	38,400	86,400	8.33	204,800
2700	8.33	4.76	7.14	80,000	40,800	91,800	8.33	212,600
2800	8.33	5.04	7.56	80,000	43,200	97,200	8.33	220,400
2900	8.33	5.32	7.98	80,000	45,600	102,600	8.33	228,200
3000	8.33	5.60	8.40	80,000	48,000	108,000	8.40	236,000
3100	8.33	5.88	8.82	80,000	50,400	113,400	8.82	243,800
3200	8.33	6.16	9.24	80,000	52,800	118,800	9.24	251,600
3300	8.33	6.44	9.66	80,000	55,200	124,200	9.66	259,400
3400	8.33	6.72	10.08	80,000	57,600	129,600	10.08	267,200
3500	8.33	7.00	10.50	80,000	60,000	135,000	10.50	275,000
3600	8.33	7.28	10.92	80,000	62,400	140,400	10.92	282,800
3700	8.33	7.56	11.34	80,000	64,800	145,800	11.34	290,600
3800	8.33	7.84	11.76	80,000	67,200	151,200	11.76	298,400
3900	8.33	8.12	12.18	80,000	69,600	156,600	12.18	306,200
4000	8.33	8.40	12.60	80,000	72,000	162,000	12.60	314,000
4100	8.33	8.68	13.02	80,000	74,400	167,400	13.02	321,800
4200	8.33	8.96	13.44	80,000	76,800	172,800	13.44	329,600
4300	8.33	9.24	13.86	80,000	79,200	178,200	13.86	337,400
4400	8.33	9.52	14.28	80,000	81,600	183,600	14.28	345,200
4500	8.33	9.80	14.70	80,000	84,000	189,000	14.70	353,000
4600	8.33	10.08	15.12	80,000	86,400	194,400	15.12	360,800
4700	8.33	10.36	15.54	80,000	88,800	199,800	15.54	368,600
4800	8.33	10.64	15.96	80,000	91,200	205,200	15.96	376,400
4900	8.33	10.92	16.38	80,000	93,600	210,600	16.38	384,200
5000	8.33	11.20	16.80	80,000	96,000	216,000	16.80	392,000

From the data in Table 6.3.10, Figures 6.3.6, 6.3.7, 6.3.8, 6.3.9 and 6.3.10 were generated:

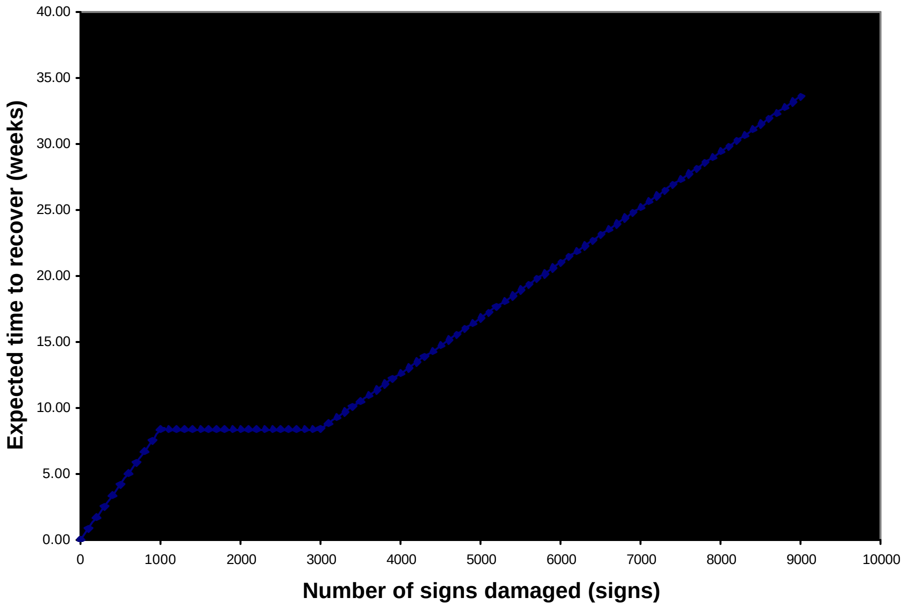

Figure 6.3.6. Expected Recovery time (weeks) Versus Signs Damaged (signs)

Figure 6.3.6 shows that the more signs that are damaged, the more time it takes to recover. At the beginning of the graph the slope is much lower due to the fact that there are signs on hand.

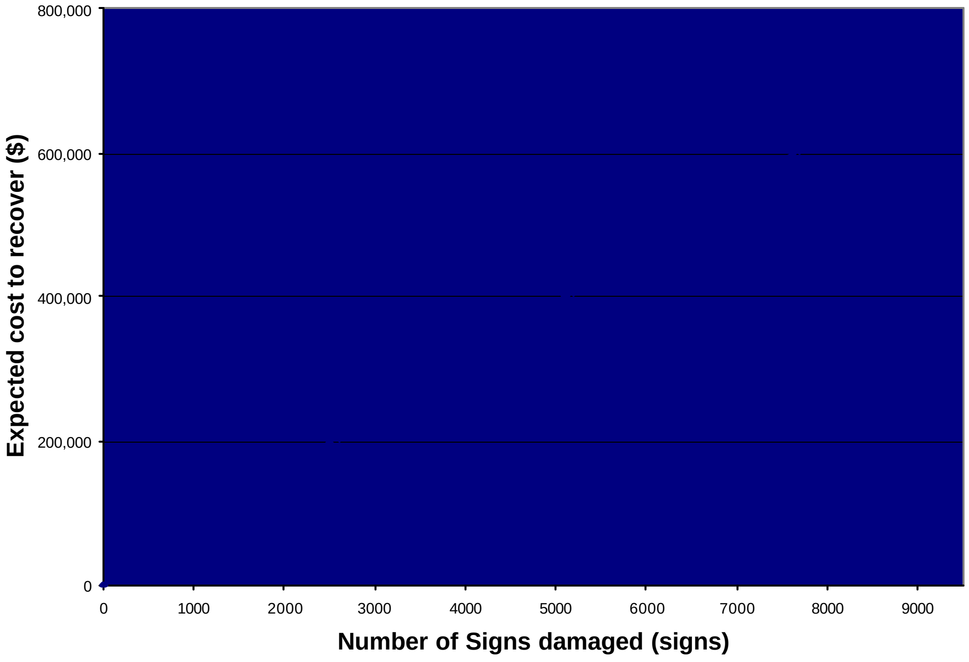

Figure 6.3.7. Expected Recovery cost ($) Versus Signs Damaged (signs)

Likewise Figure 6.3.7 shows how the cost increases as the number of signs damaged increases.

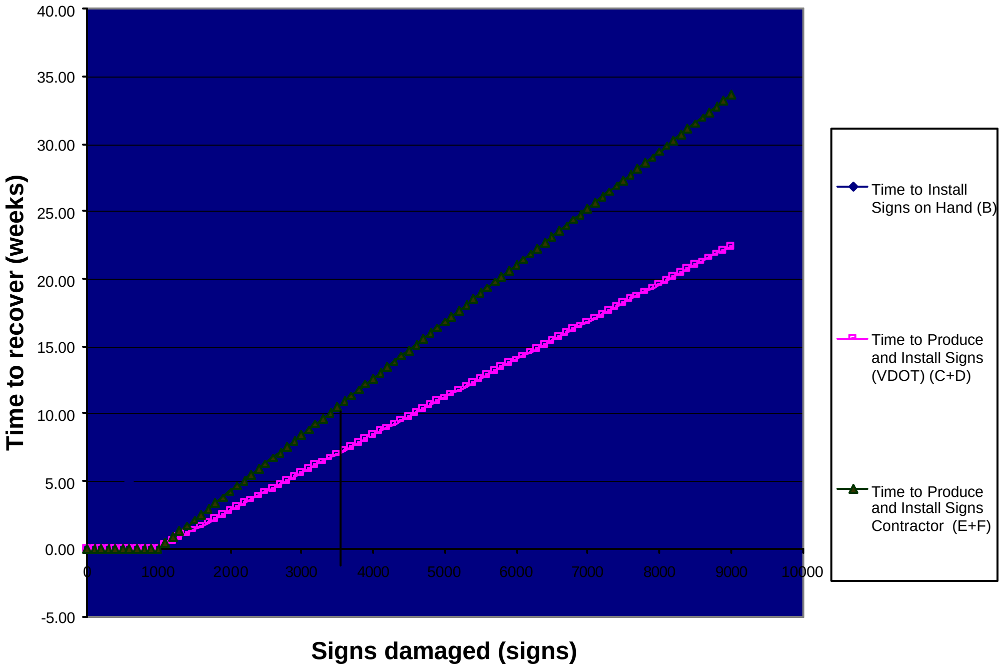

Figure 6.3.8. Recovery time (weeks) for all Three Paths in Figure 6.3.5

Figure 6.3.8 is a comparison of the three branches of Figure 6.3.3, which includes recovery time by installing existing reserves, contracting, and producing in-house. For example, if 3,500 signs were damaged, the maximum of all three paths is selected in order to determine the recovery time, which would be 10.5 weeks (Equation 3.26). The tasks are parallel. While VDOT would be installing signs from the reserves on-hand, VDOT and contractors would be producing and installing the deficit. Therefore, as seen in Figure 6.3.8, it would take VDOT approximately eight weeks to install the on-hand reserves. The remaining 2,500 signs would be distributed between the contractors and VDOT. If the contractors were assigned to produce and install 70% of the 2,500 signs according to Figure 6.3.8 they would take 10.5 weeks. The other 30% assigned to VDOT would take approximately eight weeks.

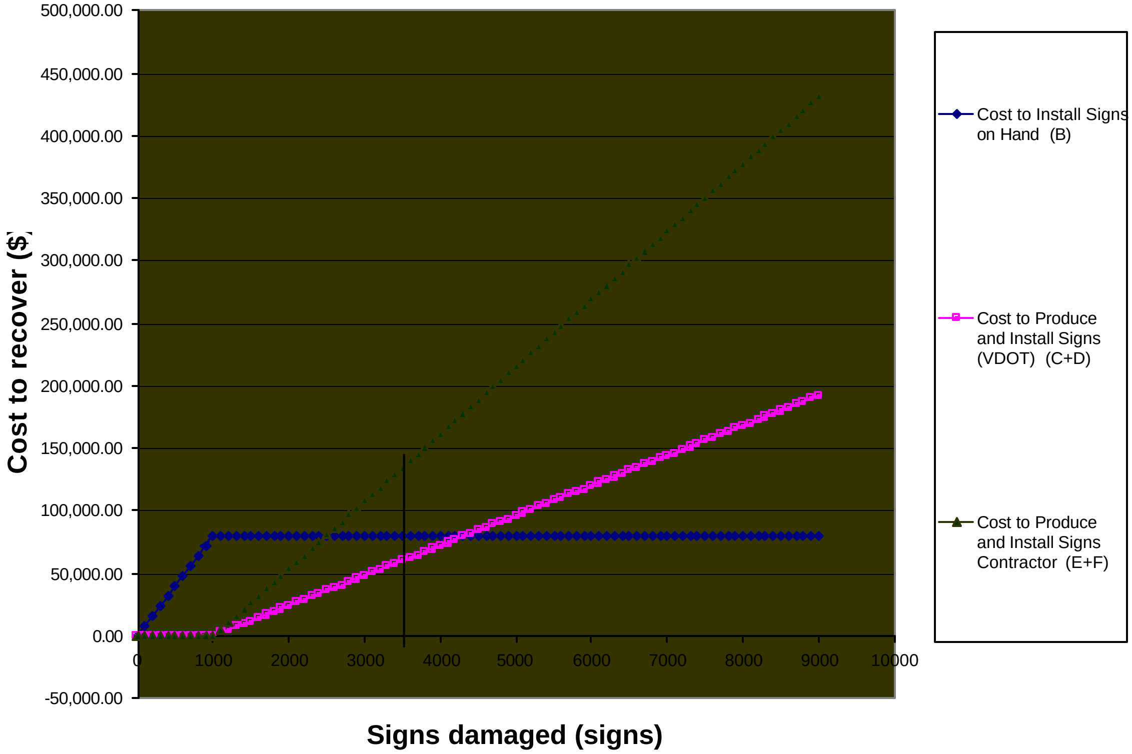

Figure 6.3.9. Recovery cost ($) for all Three Paths in Figure 6.3.3

Figure 6.3.9 compares the recovery costs of three alternatives: installing existing reserves, contracting, and producing in-house. For example, if 3,500 signs were damaged, all three paths have to be added in order to determine the recovery cost, which would be $60,000 plus $80,000 plus $135,000 for a total of $275,000 (Equation 6.3.27).

In the same manner the data is obtained to calculate the outcomes for the decision tree.

One critical issue that contributes to the recovery time is the installation time. The installation time is dependent on the number of crews installing the traffic control equipment. In Figure 6.3.10, the relationship of crews versus the installation time may be seen. Figure 6.3.10 assumes that 9,000 signs were damaged.

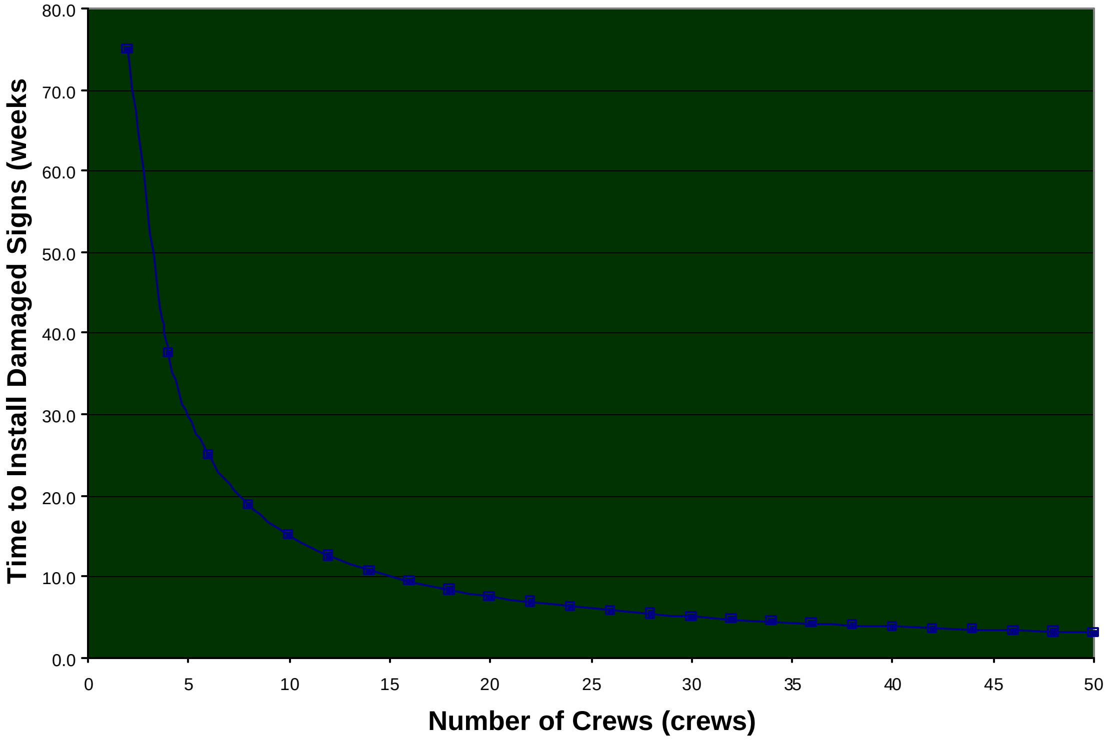

Figure 6.3.10. Time to Install Damaged Signs (weeks) versus Number of Crews (crews)

As seen in Figure 6.3.10, the more crews there are to install the damaged signs, the less time it would take to install the signs.

Pre-Hurricane Preparation Cost

The decision model contemplates two decision stages explained in the "Sequential Decision Making By Highway Agency" section. The first stage is the long-term administrative decision, such as building a warehouse that would cost $650,000 (if the annual cost is 5% of the total cost then the annualized cost would be $32,500). The second stage is the short-term operational decision, which is incrementally increasing the production of ground-mounted signs 30"x 30" by 10%.

Pre-hurricane preparation cost is determined by the cost of the long-term decision plus the short-term decision.

$C_T = C_L + C_S$ ($) Eq. 6.3.28

Where:

C_T = Pre-hurricane preparation cost ($)

C_L = Cost of implementing the long-term decision (Stage 1) ($).

C_S = Cost of implementing the short-term decision (Stage 2) ($).

C_L = Annualized cost of implementing the long-term decision.

Cost of implementing the short-term decision is the increment of signs multiplied by the cost to VDOT.

$$Short\ Term\ Cost = C_s = (A * X) * C_V \qquad (\$) \qquad \text{Eq. 6.3.29}$$

Where

A= Actual number of signs on hand in VDOT (signs).

X= Percentage of increment of production in stage 2 option (%).

C_V= Cost to VDOT producing the signs ($).

Summary

Damage and attributes are required for the development of the models. First the damage has to be assessed to determine the recovery time and the recovery cost. Then the pre-hurricane preparation cost is calculated. Once all the attributes are determined the model can be used and the folding back process of the decision tree may begin, as described in the next section.

Sequential Decision Making By Highway Agency

Introduction

In this section, a sequential decision model is explained in detail. The model is used to aid in managing reserves of damageable equipment. The first part of this section of the chapter details the assumptions and data utilized in the sequential decision making example used in this section. The second section discusses the decision model, which utilizes long-term forecast with the use of historical data. The last section shows all the calculations and results from the example and a brief explanation on how to interpret them.

Assumptions and Data

This section contains relevant information that applies directly to the model and is derived from the procedures discussed in the "Modeling Hurricane Impacts" section. In order to establish the decision models, first the influence diagrams have to be established in order to view the relationships between the decision nodes, chance nodes, states of nature and consequences.

The model is drawn from the following influence diagram, which is illustrated in Figure 6.4.1.

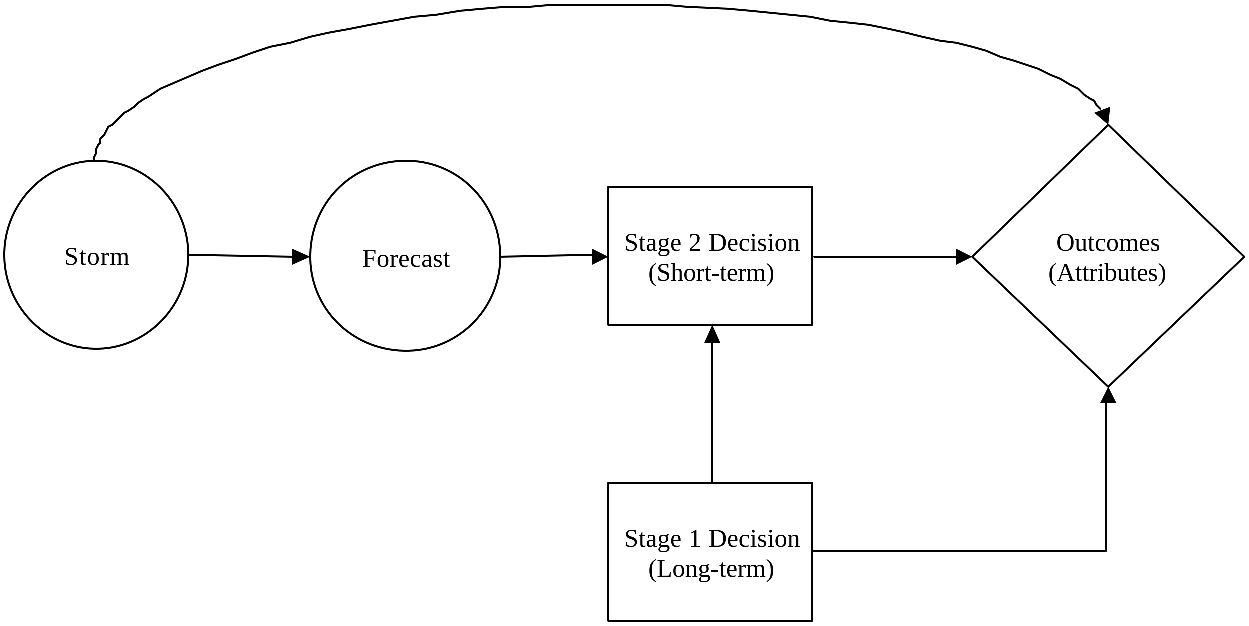

Figure 6.4.1. Influence Diagram for the Decision Model

The Stage 1 options refer to the administrative, long-term decisions and the Stage 2 options refer to the operational, short-term decisions that are made by the highway agency after receiving a seasonal hurricane forecast. The event of a storm influences the outcome and the forecast (whether it is historical or projected). Then, the event of the forecast influences the Stage 2 decision, but not the Stage 1 long-term decision, because the Stage 1 decision is made prior to any forecast. The Stage 1, long-term decision influences the Stage 2, short-term decision, because the long-term, administrative decision affects the options available at Stage 2. For example, if at Stage 1 the decision-maker decided to build a warehouse, then at Stage 2 the decision maker will not be limited by storage capacity of reserves and would therefore have the ability to increase production more than if the warehouse wasn't built. Both Stage 1 and Stage 2 decisions influence the outcome.

Once the relationships are established, one can proceed to establish the options for Stages 1 and 2.

The following information describes three different options that can be entered in the decision tree:

Stage 1, option 1: The long-term decision to implement a warehouse and the annualized cost, which is a percentage (5%) of the total cost, would be $32,500.00 (Warehouse cost – 10,000 sq. ft. at $65 per sq. ft.; 10,000 sq. ft. x $65 = $650,000). Having a new warehouse would allow greater production. In Stage 2, VDOT would decide to produce and store either 0, 10% or 20% after hearing the seasonal forecast.

Stage 1, option 2: The decision is to build a smaller warehouse. If the warehouse is half the size of the one in Stage 1, option 1, then the annualized cost would be $16,250. Because of the restricted area, VDOT cannot produce in the same quantities as option 1. Therefore, VDOT could decide in Stage 2 based on the seasonal forecast to store between a 0% or 10% level of reserves.

Stage 1, option 3: This option suggests that VDOT maintain the current capacity. With this restricted capacity VDOT could decide between much lower strategies of increasing productions prior to hurricane strike. The Stage 2 decision can be between 0% or 5%.

Summary of the data described above is shown in Table 6.4.1:

Table 6.4.1. Summary of Administrative and Operational Data Used in the Example for Decision Models

			Stage 2			
			0%	5%	10%	20%
Stage 1	Option 1	Large - 35,000	Yes	No	No	Yes
	Option 2	Small - 16,200	Yes	No	Yes	No
	Option 3	Same - 0	Yes	Yes	No	No

Hurricane Decision Model. Planning for Operation

The planning for an operation model utilizes historical data to evaluate different policies by determining the probabilities of a type of storm being the worst case scenario given a high or low hurricane season. The model described in this section is called “Planning for Operation.” “Planning for Operation” decisions are made on the basis of long historical records (climatological data).

Decision Tree for Planning for Operation

Figure 6.4.2 illustrates the plan for operation decision model.

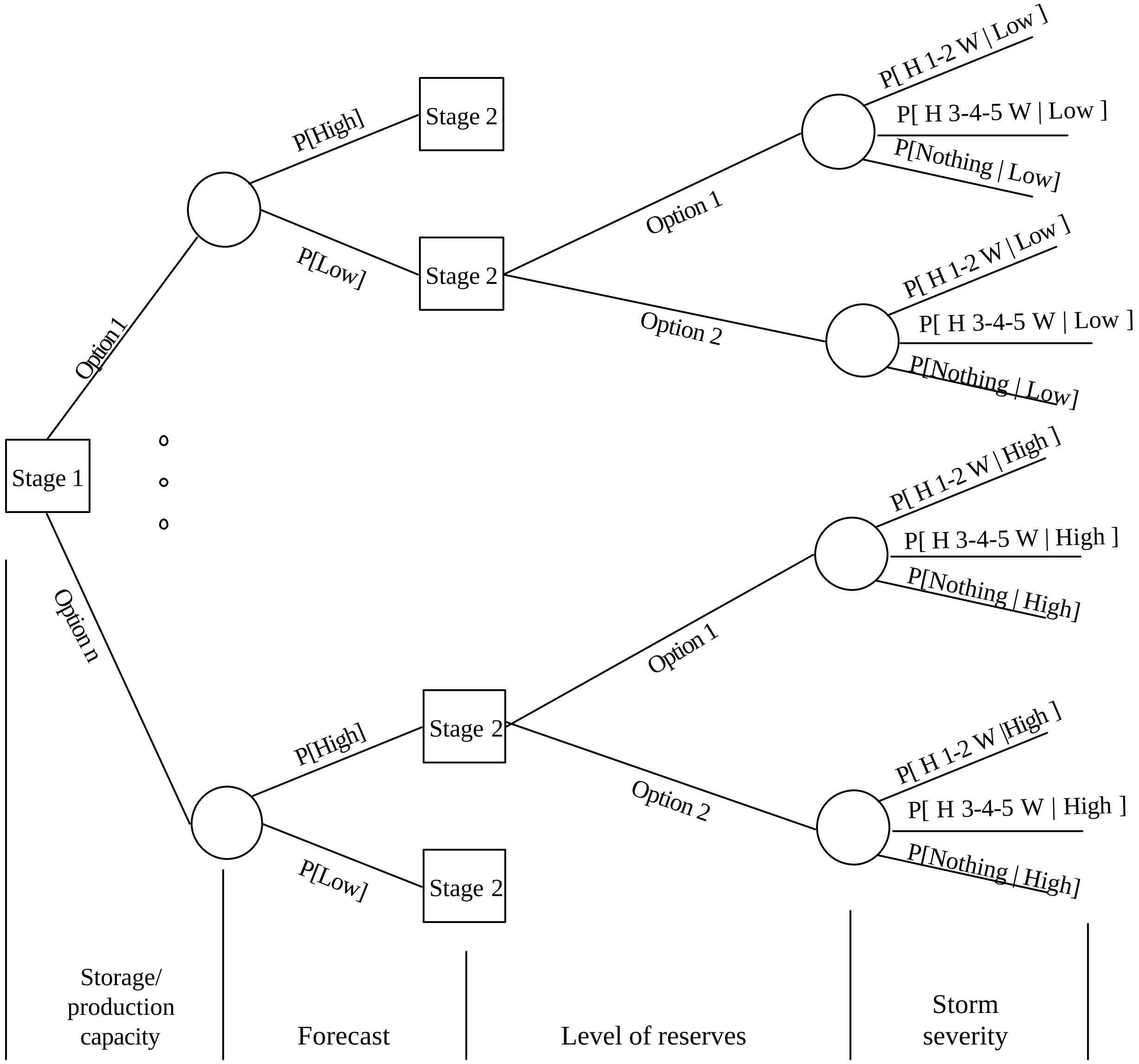

Figure 6.4.2. Sequential Decision Making Model, Planning for Operation

Notation:

$P[High] =$ The probability of a high hurricane season.

$P[Low] =$ The probability of a low hurricane season.

$P[H1-2W|High] =$ The probability that a Hurricane 1 or 2 is the worst storm given a high hurricane season.

$P[H3-4-5W|High] =$ The probability that a Hurricane 3, 4, or 5 is the worst storm given a high hurricane season.

$P[Nothing|High] =$ The probability that no storms occur given a high hurricane season.

$P[H1-2W|Low] =$ The probability that a Hurricane 1 or 2 is the worst storm given a low hurricane season.

$P[H3-4-5W|Low] =$ The probability that a Hurricane 3, 4, or 5 is the worst storm given a low hurricane season.

$P[Nothing|Low] =$ The probability that no storms occur given a low hurricane season.

The planning for an operation decision tree is divided into two Stages. The Stage 1 decision reflects the long-term decision. These include any of the administrative decisions made prior to a hurricane season such as increasing warehouse capacity. The options are described in Table 6.4.1.

After the first Stage decision there is a chance node. The chance node represents whether the year that is being considered is a high hurricane season year or a low hurricane season year. The probability of high years is 0.5 and the probability of low years is 0.5. Assume that a forecaster can discriminate seasons similar to the worst half from seasons similar to the best half based on historical record. The probabilities of high and low years are the forecast probabilities. One might take any forecast of Gray and Landsea (1999) that exceeds the climatological average to be a “high”season, for example.

Table 6.4.2. Seasonal Forecast Probabilities

Forecast	Probability
P[High]	50%
P[Low]	50%

Depending on the skill of the forecaster, one could also choose to divide the historical record as the worst 30% and best 70%, etc. For this example, the division of the record in two halves as indicated from Table 6.4.2 is used.

The second Stage of the decision tree is the operational decision. The operational decision can be increasing seasonal production by a certain percentage (5%, 10%, etc). The available options are directly dependent on the first Stage decision. The options in Stage 2 are also described in Table 6.4.1.

After the second Stage decision there is another chance node. The branches of the chance node represent the probability of certain storm type being the worst storm in a specific year given that it is a high or low hurricane season. The method of calculating the probabilities for these branches can be seen below.

In the decision model tropical storms will not be taken into consideration because the damage that they cause to highway equipment is minimal. Also, for simplification purposes, hurricanes were grouped together according to intensity. Hurricanes that have a category of 3, 4 or 5 were considered intense hurricanes, which can cause significant damage. Hurricanes that have a category 1 or 2 are less severe hurricanes.

Calculations and Results

Several calculations need to be performed in order to determine the probabilities specified in the decision model illustrated in Figure 6.4.2. The first calculation required is to determine the number of high and low years given the historical data provided by the National Hurricane Center (NHC). The data being used is detailed in Table 6.1.3.

In order to make the calculations more clear, examples are given below.

Information from Table 6.1.3 is described in Table 6.4.3:

Table 6.4.3. Sample Data from Table 6.1.3, Detailing the Number of Each Type of Hurricanes for Virginia and Florida from 1900 to 1996. (NHC, 1999)

State	Number of Hurricanes 1-2	Number of Hurricanes 3-4-5
Virginia	3	1
Florida	33	34

The years considered are 1900 to 1996. Therefore 97 years are observed. As before, consider that the forecaster can discriminate future years as the worst half of the years in the record or from the best half. The first step is to partition the historical records in two halves, high years (50% of years) and low years (50% of years). Therefore, for the example, the high years are equal to 49 (97 years * 0.50 = 49) and the low years are equal to 48, which is the remainder of the total number of years. Assume that the forecaster can decide whether the next year comes from the high or low historical year.

After determining the number of high and low years estimate the probability of a storm occurring given that it is a high or a low year.

Where:

S = Number of storms occurring from Table 6.4.3.
N = Number of high years.
L = Number of low years.
H1-2 = Hurricane 1 or 2.
H3-4-5 = Hurricane 3, 4, or 5.
H3-4-5 = Hurricane 3, 4, or 5.
H1-2W = Hurricane 1 or 2 is the worst storm.
H3-4-5W = Hurricane 3, 4, or 5 is the worst storm.

$\overline{H1-2}$ = No Hurricane 1 or 2.
$\overline{H3-4-5}$ = No Hurricane 3, 4, or 5.

For this example:

N = 49
L = 48

If the number of a type of storm exceeds or is equal to the number of worst years then the probability of a storm occurring given a high year is estimated as follows:

$$P[Storm|High\ years] = \frac{S-(S-N)-1}{N} \qquad \text{Eq. 6.4.1}$$

or

$$P\left[Storm \middle| High\ \ years\right] = \frac{N-1}{N} \qquad \text{Eq. 6.4.2}$$

For example suppose that the total number of Hurricanes 1-2 in Florida was 52; then substitute into equation 6.4.1:

$$P\left[H1-2 \middle| High\ \ years\right] = \frac{52-(52-49)-1}{49} = 0.979$$

If the number of a type of storm does not exceed the number of worst years, then we say that the probability of a storm occurring given a high year is estimated as follows:

$$P\left[Storm \middle| High\ years\right] = \frac{S}{H} \qquad \text{Eq. 6.4.3}$$

Therefore, with equation 6.4.3, the probabilities can be calculated for both Florida and Virginia.

Virginia:

$$P\left[H1-2 \middle| High\ years\right] = \frac{3}{49} = 0.062$$

$$P\left[H3-4-5 \middle| High\ \ years\right] = \frac{1}{49} = 0.020$$

Florida:

$$P\left[H1-2 \middle| High\ years\right] = \frac{33}{49} = 0.680$$

$$P\left[H3-4-5 \middle| High\ \ years\right] = \frac{34}{49} = 0.701$$

In order to calculate the probabilities of storms that occur in the low years, then:

If the number of storms minus the high years is greater or equal to the number of low years, then: First check if the probability of the number of storms minus the number of high years divided by the number of low years is greater than or equal to one. If so, then the probability of a storm occurring given a low year is estimated as follows:

$$P\left[Storm \middle| Low\ years\right] = \frac{L-1}{L} \qquad \text{Eq. 6.4.4}$$

Else:

$$P[Storm|Low\ years] = \frac{S - N}{L} \qquad \text{Eq. 6.4.5}$$

If the number of storms minus the high years is less than the number of low years, then

$$P[Storm|Low\ years] = \frac{1}{L} \qquad \text{Eq. 6.4.6}$$

For both states, Virginia and Florida, the number of storms minus the high years is not greater than the number of low years for either case. So the probabilities are as follows using equation 6.4.6:

Identical results apply to Virginia and Florida:

$$P[H1-2|Low\ years] = \frac{1}{48} = 0.021$$

$$P[H3-4-5|Low\ years] = \frac{1}{48} = 0.021$$

Table 6.4.4. Summary Data from Calculations of the Probabilities that a Storm would Strike Given a High or Low Year for Virginia and Florida Example

Storm	Virginia		Florida	
	High	Low	High	Low
H1-2	0.062	0.021	0.680	0.021
H3-4-5	0.020	0.021	0.701	0.021

Table 6.4.4 shows a data summary of all the calculations of the probabilities that various storms would occur given either a high or low year for the Virginia and Florida example.

Once these calculations have been performed, one is able to calculate the probabilities of a storm being the worst storm given a type of year (high or low).
The calculations are as follows.

The probability of a category 1or 2 hurricane as the worst storm given a that it is a high year is equal to the probability of a category 1 or 2 hurricane and not a category 3,4, or 5 hurricane given that it is a high year.

$$P[H1-2W|High\ year] = P\left[\ H1-2 \cap \overline{H3-4-5}\ |High\ year\ \right] \qquad \text{Eq. 6.4.7}$$

The previous equation can also be written as:

$$P\left[H1-2W \middle| High\ year\right] = P\left[H1-2 \middle| \overline{H3-4-5}, High\ year\right] P\left[\overline{H3-4-5} \middle| High\ year\right]$$

Eq. 6.4.8

Assuming that hurricanes of various severities are independent events, then equation (6.4.8) can be simplified as:

$$P\left[H1-2W \middle| High\ year\right] = P\left[H1-2 \middle| High\ year\right] P\left[\overline{H3-4-5} \middle| High\ year\right]$$

Eq. 6.4.9

Equation 6.4.9 can be written as follows:

$$P\left[H1-2W \middle| High\ year\right] = P\left[H1-2 \middle| High\ year\right] \left\{1-P\left[H3-4-5 \middle| High\ year\right]\right\}$$

Eq. 6.4.10

The probability of a category 1or 2 hurricane as the worst storm given that it is a low year is equal to the probability of a category 1or 2 hurricane and not a category 3,4, or 5 hurricane given that it is a low year.

$$P\left[H1-2W \middle| Low\ year\right] = P\left[H1-2 \cap \overline{H3-4-5} \middle| Low\ year\right]$$

Eq. 6.4.11

Equation 6.4.11 can be written as follows:

$$P\left[H1-2W \middle| Low\ year\right] = P\left[H1-2 \middle| \overline{H3-4-5}, Low\ year\right] P\left[\overline{H3-4-5} \middle| Low\ year\right]$$

Eq. 6.4.12

Assuming that hurricanes of various severities are independent events, then equation (6.4.12) can be simplified as:

$$P\left[H1-2W \middle| Low\ year\right] = P\left[H1-2 \middle| Low\ year\right] P\left[\overline{H3-4-5} \middle| Low\ year\right]$$

Eq. 6.4.13

Equation 6.4.13 can be written as follows:

$$P\left[H1-2W \middle| Low\ year\right] = P\left[H1-2 \middle| Low\ year\right] \left\{1-P\left[H3-4-5 \middle| Low\ year\right]\right\}$$

Eq. 6.4.14

The probability of a Category 3,4, or 5 Hurricane as the worst storm given that it is a high year is equal to the probability of a Category 3,4, or 5 Hurricane and not a Category 1or 2 Hurricane given that it is a high year. The equation can be written as follows:

$$P\left[H3-4-5W \middle| High\ \ year\right] = P\left[H3-4-5 \middle| High\ \ year\right]\left\{1-P\left[H1-2 \middle| High\ \ year\right]\right\} \qquad \text{Eq. 6.4.15}$$

Eq. 6.4.15 is derived using the same method utilized in deriving Eq. 6.4.10.

The probability of a Category 3,4, or 5 Hurricane as the worst storm given that it is a low year is equal to the probability of a Category 3,4, or 5 Hurricane and not a Category 1or 2 Hurricane given that it is a low year. The equation can be written as follows:

$$P\left[H3-4-5W \middle| Low\ year\right] = P\left[H3-4-5 \middle| Low\ year\right]\left\{1-P\left[H1-2 \middle| Low\ year\right]\right\} \qquad \text{Eq. 6.4.16}$$

Eq. 6.4.16 is derived using the same method utilized in deriving Eq. 6.4.14.

In order to calculate the probability of nothing happening for high and low years then:

The probability of nothing happening given a high year is equal to one minus the result from equation 6.4.10 and the equation 6.4.15:

$$P\left[Nothing \middle| High\ \ years\right] = 1-P\left[H1-2W \middle| High\ \ years\right]-P\left[H3-4-5W \middle| High\ \ years\right] \qquad \text{Eq. 6.4.17}$$

The probability of nothing happening given a high year is equal to one minus the result from equation 6.4.14 and the equation 6.4.16:

$$P\left[Nothing \middle| Low\ years\right] = 1-P\left[H1-2W \middle| Low\ years\right]-P\left[H3-4-5W \middle| Low\ years\right] \qquad \text{Eq. 6.4.18}$$

Using equations 6.4.10, 6.4.14, 6.4.15, 6.4.16, 6.4.17, and 6.4.18, the following results can be derived for both Virginia and Florida, which are summarized in Table 6.4.5:

Table 6.4.5. Summary of Probability Results Used in Decision Model for Virginia and Florida Examples (Storm Severity Probabilities)

	Nothing		Hurricane 1-2 is worst		Hurricane 3-4-5 is worst	
State	High (Eq. 6.4.18)	Low (Eq. 6.4.17)	High (Eq.6.4.10)	Low (Eq. 6.4.14)	High (Eq. 6.4.15)	Low (Eq. 6.4.16)
Virginia	0.920	0.959	0.061	0.021	0.019	0.021
Florida	0.573	0.959	0.203	0.021	0.224	0.021

Once all the data is gathered, proceed to do all the calculations using the decision model. The decision tree data is shown in Table 6.4.6, and the chance node probabilities are given in Tables 6.4.2 and 6.4.5:

Table 6.4.6. Summary of Decision Model Data for Decision Model No. 1, Planning for Operation

Stage 1	Season	Stage2	Storm	Preparation Cost ($)	Cost to recover ($)	Time to recover (weeks)
Option 1	High	Option 1	Nothing	32,500	0	0.00
Option 1	High	Option 1	H 1-2 W	32,500	420,050	9.52
Option 1	High	Option 1	H 3-4-5 W	32,500	1,019,000	26.29
Option 1	High	Option 2	Nothing	48,500	0	0.00
Option 1	High	Option 2	H 1-2 W	48,500	390,050	8.68
Option 1	High	Option 2	H 3-4-5 W	48,500	839,000	21.25
Option 1	Low	Option 1	Nothing	32,500	0	0.00
Option 1	Low	Option 1	H 1-2 W	32,500	420,050	9.52
Option 1	Low	Option 1	H 3-4-5 W	32,500	1,019,000	26.29
Option 1	Low	Option 2	Nothing	48,500	0	0.00
Option 1	Low	Option 2	H 1-2 W	48,500	390,050	8.68
Option 1	Low	Option 2	H 3-4-5 W	48,500	989,000	25.45
Option 2	High	Option 1	Nothing	16,250	0	0.00
Option 2	High	Option 1	H 1-2 W	16,250	420,050	9.52
Option 2	High	Option 1	H 3-4-5 W	16,250	1,019,000	26.29
Option 2	High	Option 2	Nothing	24,250	0	0.00
Option 2	High	Option 2	H 1-2 W	24,250	405,050	9.10
Option 2	High	Option 2	H 3-4-5 W	24,250	1,004,000	25.87
Option 2	Low	Option 1	Nothing	16,250	0	0.00
Option 2	Low	Option 1	H 1-2 W	16,250	420,050	9.52
Option 2	Low	Option 1	H 3-4-5 W	16,250	1,019,000	26.29
Option 2	Low	Option 2	Nothing	24,250	0	0.00
Option 2	Low	Option 2	H 1-2 W	24,250	405,050	9.10
Option 2	Low	Option 2	H 3-4-5 W	24,250	1,004,000	25.87
Option 3	High	Option 1	Nothing	0	0	0.00
Option 3	High	Option 1	H 1-2 W	0	420,050	9.52
Option 3	High	Option 1	H 3-4-5 W	0	1,019,000	26.29
Option 3	High	Option 2	Nothing	4,000	0	0.00
Option 3	High	Option 2	H 1-2 W	4,000	412,550	9.31
Option 3	High	Option 2	H 3-4-5 W	4,000	1,011,500	26.08
Option 3	Low	Option 1	Nothing	0	0	0.00
Option 3	Low	Option 1	H 1-2 W	0	420,050	9.52
Option 3	Low	Option 1	H 3-4-5 W	0	1,019,000	26.29
Option 3	Low	Option 2	Nothing	4,000	0	0.00
Option 3	Low	Option 2	H 1-2 W	4,000	412,550	9.31
Option 3	Low	Option 2	H 3-4-5 W	4,000	1,011,500	26.08

The first computation in the decision model is to do all the calculations for Stage 2 in the decision tree.

The solution procedure begins by calculating the expected values at the Stage 2 decision nodes. In Figure 6.4.3 illustrates a section of one of the decision nodes at Stage 2.

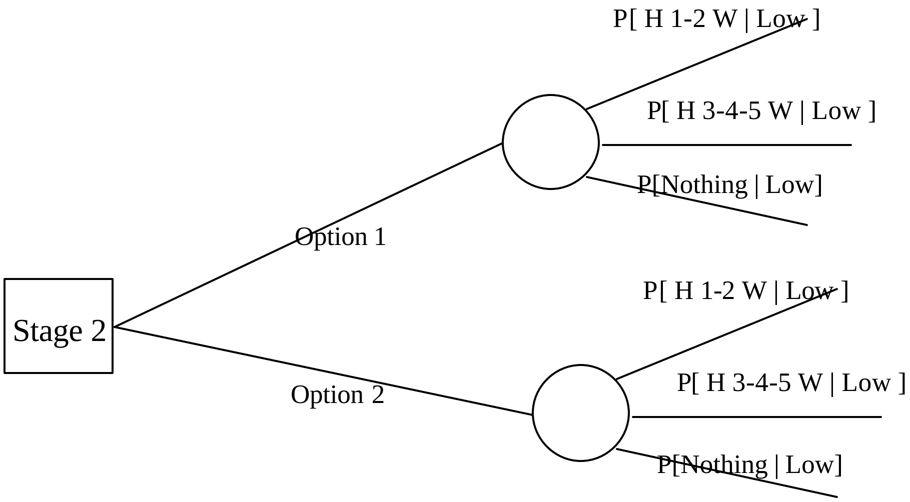

Figure 6.4.3. Diagram of Stage 2 Decision of the Decision Model

The evaluations for the decision tree were only conducted for ground-mounted signs. Different times and cost to produce and install apply to different types of traffic-control equipment. Results will vary accordingly. Each attribute, preparation cost, recovery time, and recovery cost is multiplied by the corresponding branch probability to estimate the expected value of payoff/outcome.

The results can be detailed in Table 6.4.7. As seen in Table 6.4.7, each path leading to each decision is calculated.

Table 6.4.7. Calculations and Results of Expected Values (Pre-Hurricane Preparation Cost, Recovery time and Recovery cost) at Stage 2 in the Decision Model

Stage 1	Season	P[Forecast]	Stage2	Storm	P(Storm is worst)	Preparation Cost ($)	Cost to recover ($)	Time to recover (weeks)	E(Preparation Cost) ($)	E(Cost to recover) ($)	E(Time to recover) (weeks)
Option 1	High	0.5	Option 1	Nothing	0.573	32,500	0	0.00	32,500	313,745	7.83
Option 1	High	0.5	Option 1	H 1-2 W	0.203	32,500	420,050	9.52			
Option 1	High	0.5	Option 1	H 3-4-5 W	0.224	32,500	1,019,000	26.29			
Option 1	High	0.5	Option 2	Nothing	0.573	48,500	0	0.00	48,500	267,315	6.53
Option 1	High	0.5	Option 2	H 1-2 W	0.203	48,500	390,050	8.68			
Option 1	High	0.5	Option 2	H 3-4-5 W	0.224	48,500	839,000	21.25			
Option 1	Low	0.5	Option 1	Nothing	0.959	32,500	0	0.00	32,500	29,658	0.74
Option 1	Low	0.5	Option 1	H 1-2 W	0.021	32,500	420,050	9.52			
Option 1	Low	0.5	Option 1	H 3-4-5 W	0.021	32,500	1,019,000	26.29			
Option 1	Low	0.5	Option 2	Nothing	0.959	48,500	0	0.00	48,500	28,421	0.70
Option 1	Low	0.5	Option 2	H 1-2 W	0.021	48,500	390,050	8.68			
Option 1	Low	0.5	Option 2	H 3-4-5 W	0.021	48,500	989,000	25.45			
Option 2	High	0.5	Option 1	Nothing	0.573	16,250	0	0.00	16,250	313,745	7.83
Option 2	High	0.5	Option 1	H 1-2 W	0.203	16,250	420,050	9.52			
Option 2	High	0.5	Option 1	H 3-4-5 W	0.224	16,250	1,019,000	26.29			
Option 2	High	0.5	Option 2	Nothing	0.573	24,250	0	0.00	24,250	307,333	7.65
Option 2	High	0.5	Option 2	H 1-2 W	0.203	24,250	405,050	9.10			
Option 2	High	0.5	Option 2	H 3-4-5 W	0.224	24,250	1,004,000	25.87			
Option 2	Low	0.5	Option 1	Nothing	0.959	16,250	0	0.00	16,250	29,658	0.74
Option 2	Low	0.5	Option 1	H 1-2 W	0.021	16,250	420,050	9.52			
Option 2	Low	0.5	Option 1	H 3-4-5 W	0.021	16,250	1,019,000	26.29			
Option 2	Low	0.5	Option 2	Nothing	0.959	24,250	0	0.00	24,250	29,040	0.72
Option 2	Low	0.5	Option 2	H 1-2 W	0.021	24,250	405,050	9.10			
Option 2	Low	0.5	Option 2	H 3-4-5 W	0.021	24,250	1,004,000	25.87			
Option 3	High	0.5	Option 1	Nothing	0.573	0	0	0.00	0	313,745	7.83
Option 3	High	0.5	Option 1	H 1-2 W	0.203	0	420,050	9.52			
Option 3	High	0.5	Option 1	H 3-4-5 W	0.224	0	1,019,000	26.29			
Option 3	High	0.5	Option 2	Nothing	0.573	4,000	0	0.00	4,000	310,539	7.74
Option 3	High	0.5	Option 2	H 1-2 W	0.203	4,000	412,550	9.31			
Option 3	High	0.5	Option 2	H 3-4-5 W	0.224	4,000	1,011,500	26.08			
Option 3	Low	0.5	Option 1	Nothing	0.959	0	0	0.00	0	29,658	0.74
Option 3	Low	0.5	Option 1	H 1-2 W	0.021	0	420,050	9.52			
Option 3	Low	0.5	Option 1	H 3-4-5 W	0.021	0	1,019,000	26.29			
Option 3	Low	0.5	Option 2	Nothing	0.959	4,000	0	0.00	4,000	29,349	0.73
Option 3	Low	0.5	Option 2	H 1-2 W	0.021	4,000	412,550	9.31			
Option 3	Low	0.5	Option 2	H 3-4-5 W	0.021	4,000	1,011,500	26.08			

Table 6.4.7 illustrates the expected costs and time at Stage 2. After the calculations, no policy drops out. All solutions are Pareto optimal. Pareto optimal describes a solution for which one can not improve one objective function without degrading another function (Haimes, 1998).

For example, at Stage 2, the decision-maker has to decide between the two policies; given that at Stage 1 the forecast is high. Table 6.4.8 details the information for one of the branches at Stage 2, which has to be evaluated to determine what is the optimal decision at that decision node.

Table 6.4.8. Abstract from Table 6.4.7 to Show Branch Comparison to Determine Pareto Optimal Solutions

Stage 1	Season	Stage 2	E[Preparation Cost] ($)	E[Recovery cost] ($)	E[Recovery time] (weeks)
Option 1	High	Option 1	32,500	45,160	1.09
Option 1	High	Option 2	48,500	39,860	0.94

Using Table 6.4.8, when one compares Option 1 and 2 at Stage 2, after one has chosen Option 1 at Stage 1, it can be observed that for Stage 2 option 1 the expected preparation cost is lower than Option 2. It is also observed that the expected recovery cost and the expected recovery time Option 1 is higher than Option 2. Therefore, the decision-maker cannot decide between the two options making them both feasible solutions or Pareto optimal solutions. All the branches at the decision stage have to be evaluated in a similar manner.

Due to the fact that all the solutions are Pareto optimal, in order to calculate the expected values at Stage 1, combinations of all possibilities have to be performed, as follows:

First, for each of the solutions, the expected values at Stage 2 are multiplied by the corresponding seasonal forecast probabilities. The calculations yield Table 6.4.9:

Table 6.4.9. Initial Calculations at Stage 1 to Proceed with the Combinations

Stage 1	**Forecast**	**P(F)**	**Stage2**	**At Stage 2**			**At Stage 1**		
				E(Preparation Cost) ($)	**E(Cost to recover) ($)**	**E(Time to recover) Weeks)**	**E(Preparation Cost) ($)**	**E(Cost to recover) ($)**	**E(Time to recover) (Weeks)**
Option 1	High	0.5	Option 1	32,500	313,745	7.83	16,250	156,873	3.91
Option 1	High	0.5	Option 2	48,500	267,315	6.53	24,250	133,658	3.26
Option 1	Low	0.5	Option 1	32,500	29,658	0.74	16,250	14,829	0.37
Option 1	Low	0.5	Option 2	48,500	28,421	0.70	24,250	14,211	0.35
Option 2	High	0.5	Option 1	16,250	313,745	7.83	8,125	156,873	3.91
Option 2	High	0.5	Option 2	24,250	307,333	7.65	12,125	153,667	3.82
Option 2	Low	0.5	Option 1	16,250	29,658	0.74	8,125	14,829	0.37
Option 2	Low	0.5	Option 2	24,250	29,040	0.72	12,125	14,520	0.36
Option 3	High	0.5	Option 1	0	313,745	7.83	0	156,873	3.91
Option 3	High	0.5	Option 2	4,000	310,539	7.74	2,000	155,270	3.87
Option 3	Low	0.5	Option 1	0	29,658	0.74	0	14,829	0.37
Option 3	Low	0.5	Option 2	4,000	29,349	0.73	2,000	14,674	0.36

After conducting all the probability multiplication, proceed to do all the policy combinations. All possible attribute combinations have to be considered.

Table 6.4.10. Combination Calculations for Pre-Hurricane Preparation Cost, Recovery Time and Recovery Cost at Stage 1.

Stage 1	Stage 2				E(Preparation Cost)
	High		Low		
Option 1	Option 1	16,250	Option 1	16,250	32,500
	Option 1	16,250	Option 2	24,250	40,500
	Option 2	24,250	Option 1	16,250	40,500
	Option 2	24,250	Option 2	24,250	48,500
Option 2	Option 1	8,125	Option 1	8,125	16,250
	Option 1	8,125	Option 2	12,125	20,250
	Option 2	12,125	Option 1	8,125	20,250
	Option 2	12,125	Option 2	12,125	24,250
Option 3	Option 1	0	Option 1	0	0
	Option 1	0	Option 2	2,000	2,000
	Option 2	2,000	Option 1	0	2,000
	Option 2	2,000	Option 2	2,000	4,000

Stage 1	Stage 2				E(Recovery Time)
	High		Low		
Option 1	Option 1	156,873	Option 1	14,829	171,702
	Option 1	156,873	Option 2	14,211	171,083
	Option 2	133,658	Option 1	14,829	148,487
	Option 2	133,658	Option 2	14,211	147,868
Option 2	Option 1	156,873	Option 1	14,829	171,702
	Option 1	156,873	Option 2	14,520	171,392
	Option 2	153,667	Option 1	14,829	168,496
	Option 2	153,667	Option 2	14,520	168,186
Option 3	Option 1	156,873	Option 1	14,829	171,702
	Option 1	156,873	Option 2	14,674	171,547
	Option 2	155,270	Option 1	14,829	170,099
	Option 2	155,270	Option 2	14,674	169,944

Stage 1	Stage 2				E(Recovery Cost)
	High		Low		
Option 1	Option 1	3.91	Option 1	0.37	4.28
	Option 1	3.91	Option 2	0.35	4.27
	Option 2	3.26	Option 1	0.37	3.63
	Option 2	3.26	Option 2	0.35	3.62
Option 2	Option 1	3.91	Option 1	0.37	4.28
	Option 1	3.91	Option 2	0.36	4.27
	Option 2	3.82	Option 1	0.37	4.19
	Option 2	3.82	Option 2	0.36	4.18
Option 3	Option 1	3.91	Option 1	0.37	4.28
	Option 1	3.91	Option 2	0.36	4.28
	Option 2	3.87	Option 1	0.37	4.24
	Option 2	3.87	Option 2	0.36	4.23

There are twelve policies to be evaluated after all the attribute combinations have been considered.

Once all the expected values at Stage 1 are calculated, a comparison of the policies can be conducted:

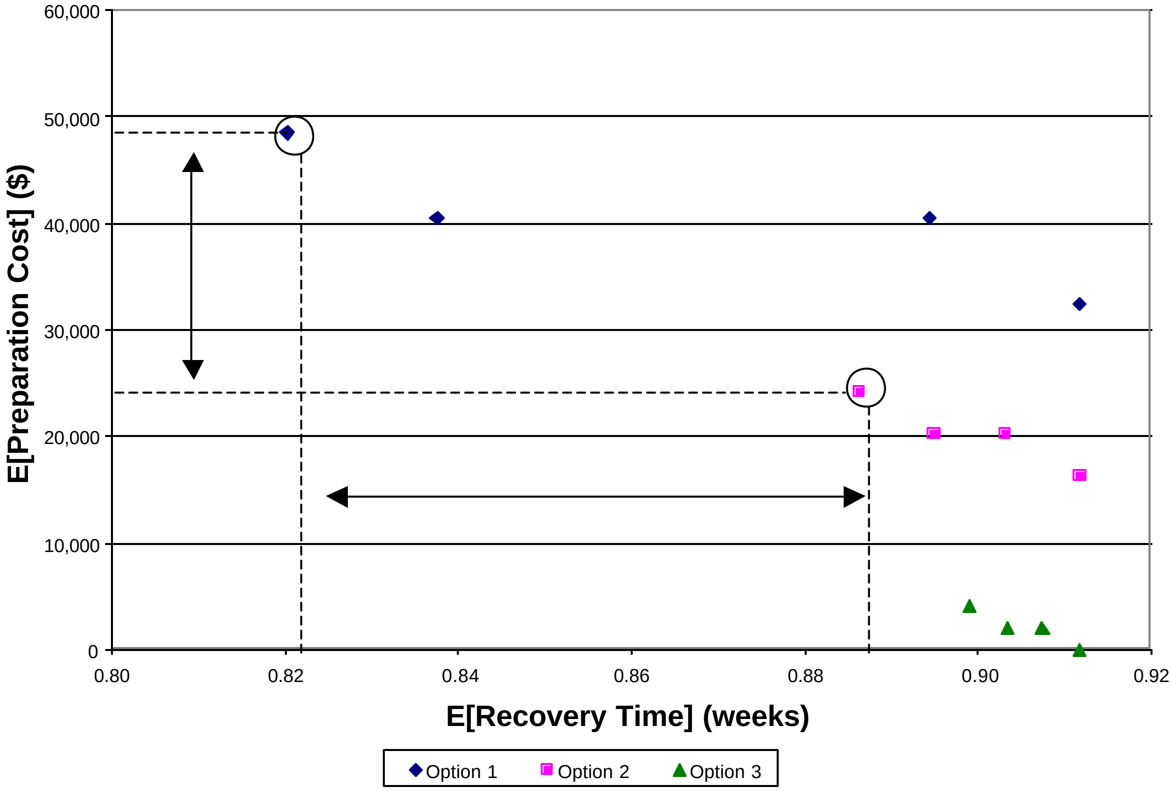

Figure 6.4.4. Pre-Hurricane Preparation Cost ($) Versus Recovery Time (weeks) for Virginia

In Figure 6.4.4 there are many policies to consider. The highway agency has to evaluate the different trade-offs such as recovering in 0.82 weeks while investing almost $50,000, or recovering in 0.89 weeks while investing about $25,000.

Figure 6.4.5 considers another trade-off comparison.

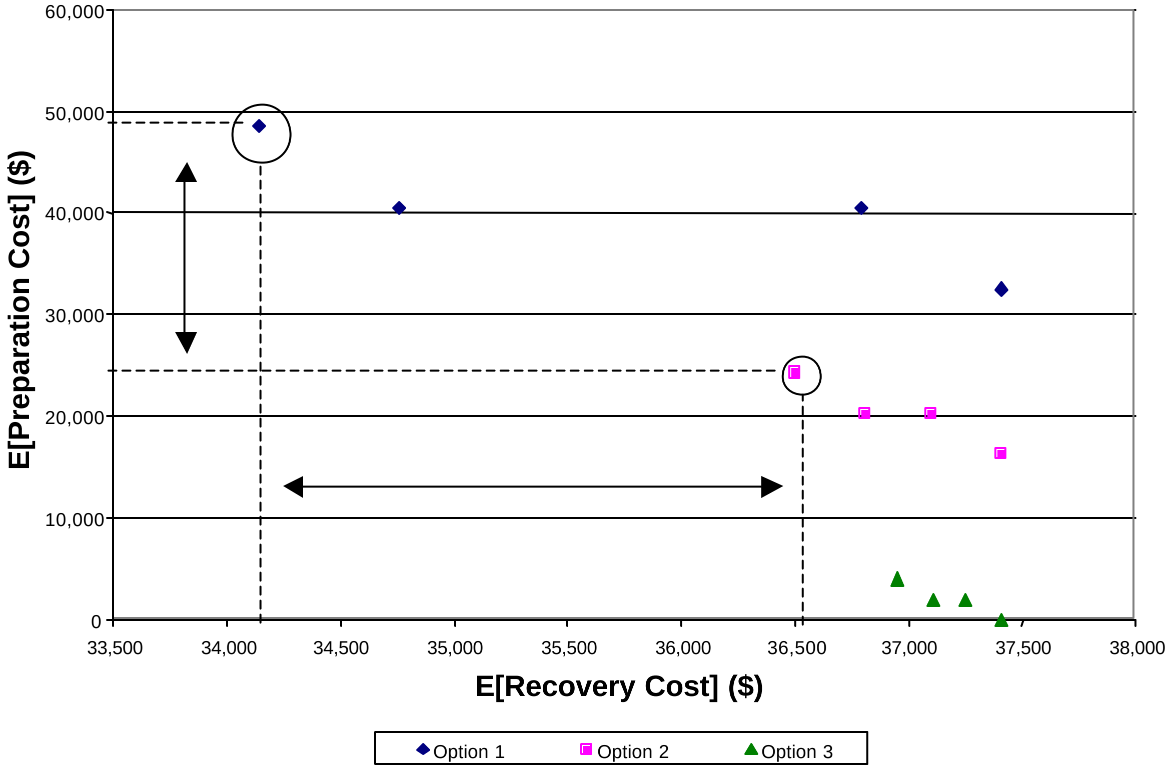

Figure 6.4.5. Pre-Hurricane Preparation Cost ($) Versus Recovery Cost ($) for Virginia

In Figure 6.4.5, one trade-off can be to invest almost $50,000 to prepare for the hurricane while having to spend $34,200 later, versus investing only $25,000 now while having to pay $36,500 later.

With both Figure 6.4.4 and Figure 6.4.5, trade-offs can be examined to establish the preferred policies. The highway agency can determine whether to invest more initially and implement a specific policy, or to spend more funds later to recover.

The results shown in Figures 6.4.4 and 6.4.5 were derived from the information attained from the production and installation rates, potential damage, seasonal forecasts, and the historical information provided for Virginia.

Therefore, changes in production or installation capabilities, such as increasing the number of crews, would decrease the recovery time, which in turn would change the results attained in Figures 6.4.4 and 6.4.5.

Another critical factor is the percentage of the number of damaged signs assigned to VDOT and to the contractors. If VDOT is assigned to produce 70% and the contractors the remaining 30% of the signs, the expected recovery time would increase, but the recovery cost would decrease as seen in Figures 6.4.6 and 6.4.7.

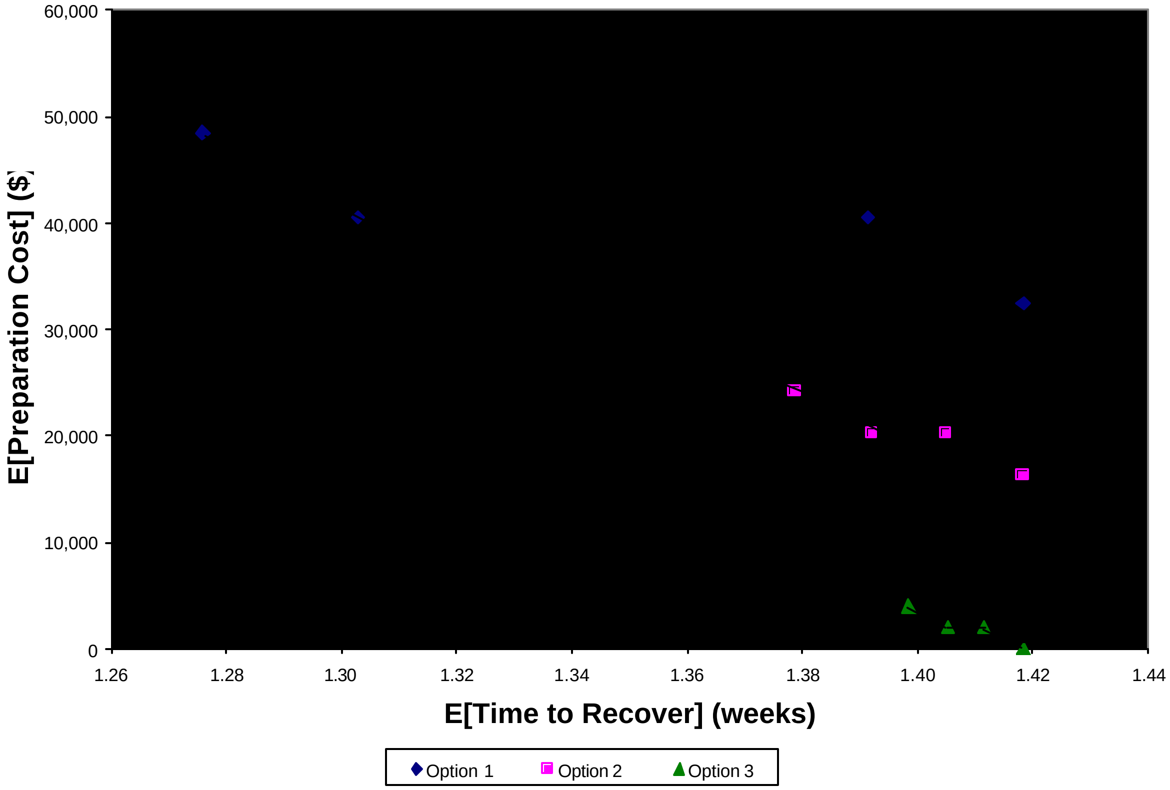

Figure 6.4.6. Pre-Hurricane Preparation Cost ($) Versus Recovery Time (weeks) for Virginia Assigning 70% of Damaged Signs to be Produced and Installed by VDOT and the Remaining Signs to Contractors (Solid Line Denotes Pareto-Optimal Policies)

Figure 6.4.6 shows the results from the decision tree where 70% of the production to replace damaged signs was assigned to VDOT and 30% assigned to contractors. Comparing Figure 6.4.6 to Figure 6.4.4, one is able to see that the recovery time is greater when VDOT produces and installs the signs. The results are a reflection of the installation capabilities considered for this example. If the number of crews was increased, the recovery time would decrease significantly.

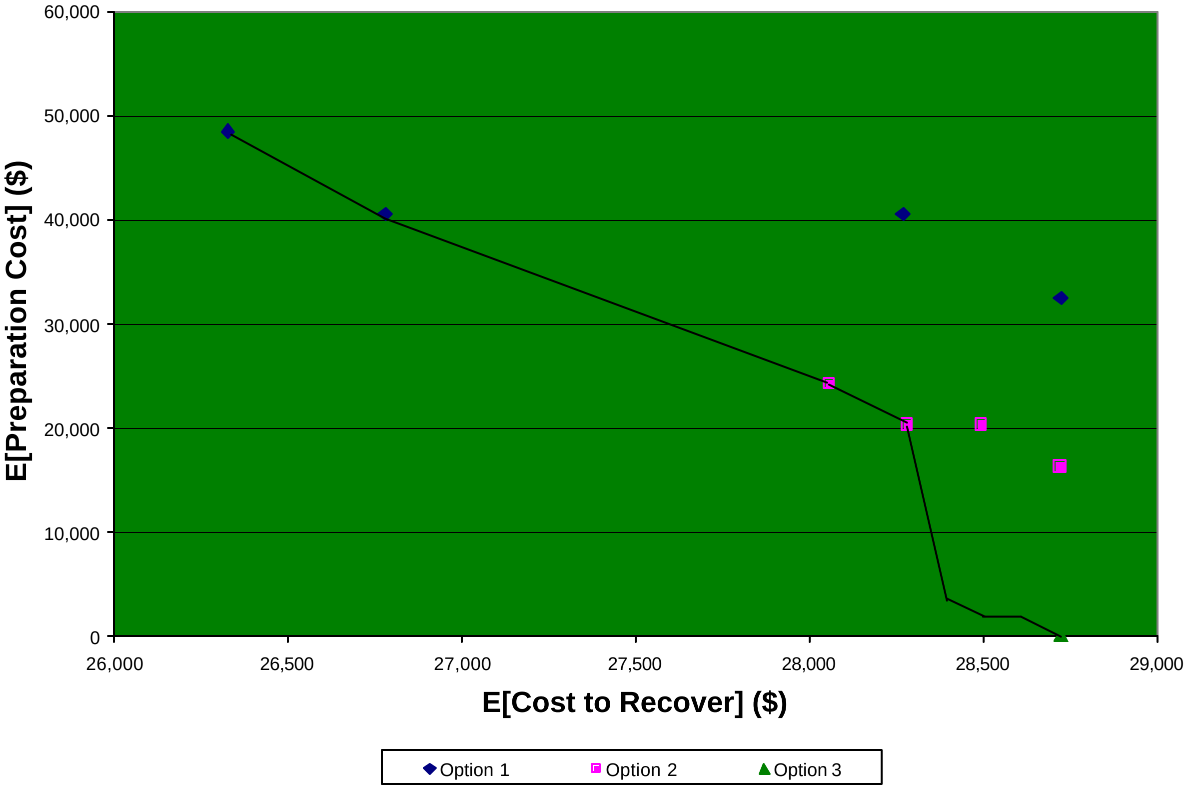

Figure 6.4.7. Pre-Hurricane Preparation Cost ($) Versus Recovery Cost ($) for Virginia Assigning 70% of Damaged Signs to be Produced and Installed by VDOT and the Remaining Signs to Contractors (Solid Line Denotes Pareto Optimal Policies)

Figure 6.4.7 shows the results from the decision tree where 70% of the production to replace damaged signs was assigned to VDOT and 30% assigned to contractors. Comparing Figure 6.4.7 to Figure 6.4.5, one is able to see that the recovery cost is less when VDOT produces and installs the signs. The results are a reflection of the production and installation costs that were considered for this example. VDOT's cost of production and installation is significantly lower than the contractor's cost of production and installation.

Another significant factor that affects the results is how prone a region has been to hurricanes. If one were to analyze the results of the decision tree with the information for Florida detailed in the "Calculation and Results" subsection of the "Sequential Decision Making By Highway Agency Section", the results of the decision tree would be those illustrated in Figures 6.4.8 and 6.4.9.

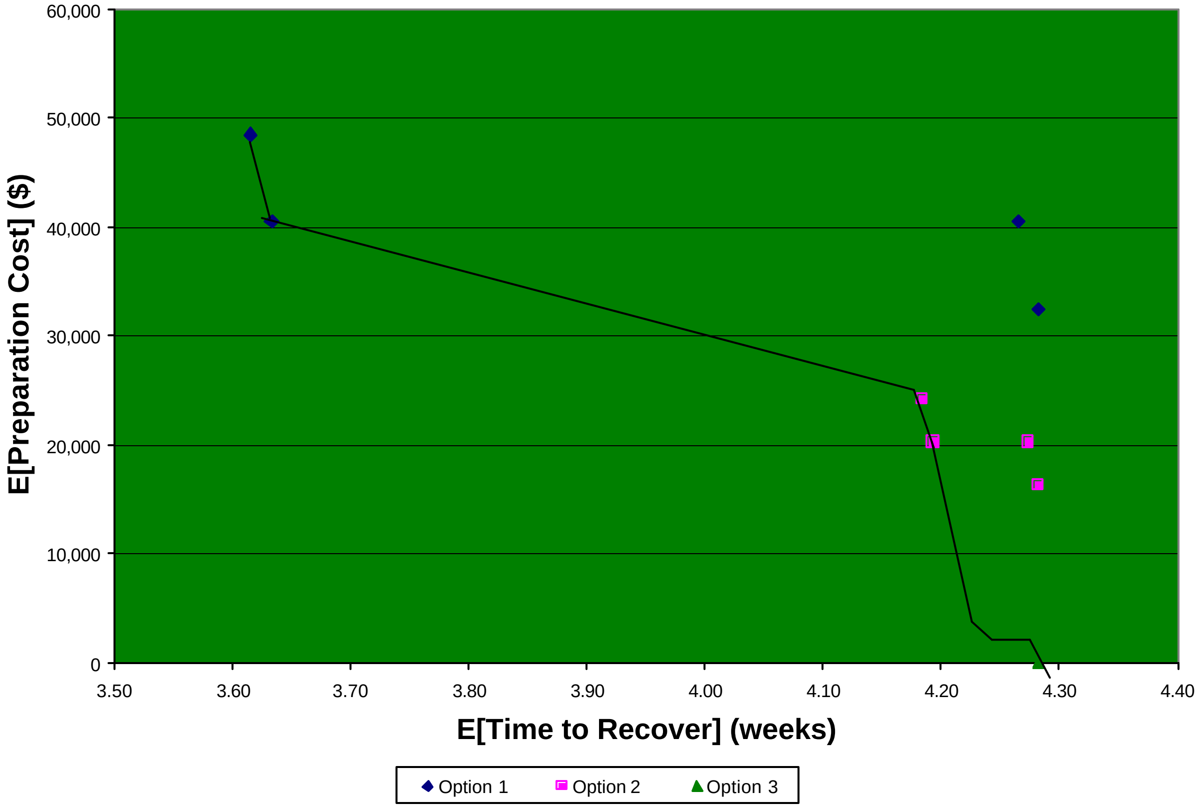

Figure 6.4.8. Pre-Hurricane Preparation Cost ($) Versus Recovery time (weeks) for Florida (Solid Line Indicates Pareto Optimal Policies)

Figure 6.4.8, shows that the expected recovery time is greater for Florida than Virginia because Florida is more prone to hurricanes.

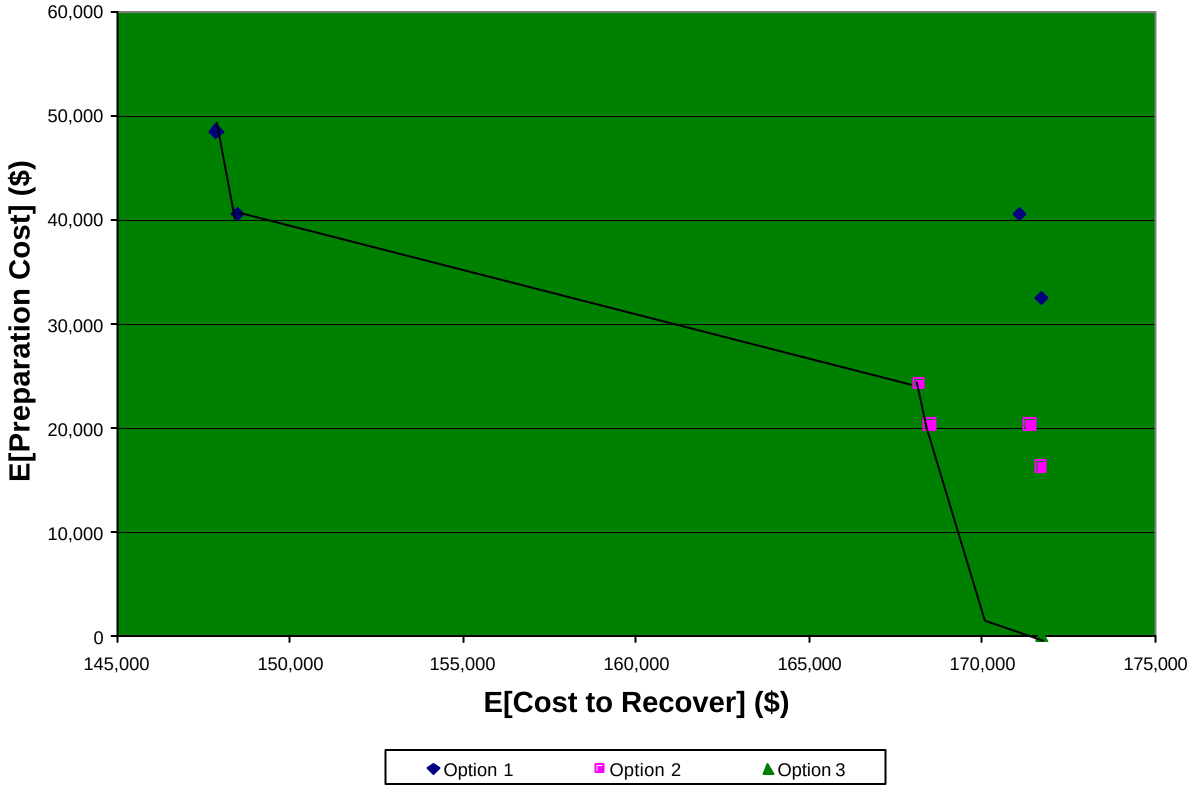

Figure 6.4.9. Pre-Hurricane Preparation Cost ($) Versus Recovery Cost ($) for Florida (Solid Line Indicates Pareto Optimal Policies)

As seen in Figure 6.4.9, due to the fact that the probabilities of hurricane landfall are greater in Florida than in Virginia, the expected recovery cost is greater for Florida.

There are many factors to be considered in order to prepare for hurricane season. The decision tree model is a tool that will aid the highway agency in discerning among the different possibilities and consequently assist in preparing for hurricane landfall.

Conclusions

In order to make a good assessment for managing reserves, the agency should have all the forecast and cost information available. As can be seen, long-term and short-term decision-making in regard to equipment reserves involves numerous models and criteria. How much should VDOT produce? To what extent should VDOT be prepared in case of a hurricane? There are several trade-offs that have to be considered. VDOT has to determine whether it should pay now (preparation cost) or pay later (recovery cost), a trade-off was established through the decision tree model. Another trade-off that can be assessed in the decision tree model is preparation cost versus the recovery time. The decision tree gives ideas on how to plan for the short-term and long-term. A sequence of decisions can be analyzed using this method.

A critical finding is that the recovery time is affected mainly by the installation time. The installation time is dependent on the number of crews available for installations and on the amount of time spent determining where the signs need to be installed. Therefore one recommendation would be to train more crews in the installation of signs, signals and lights.

As previously stated, impairment of traffic-control equipment reduces the ability to transport people, equipment, and resources needed for the restoration of infrastructure. Without signs to direct travelers and lights to illuminate roads, highways can be confusing and dangerous. After a hurricane, businesses, government, and educational facilities remain closed until some level of recovery is achieved. Months or even years could pass before a community can return to its original state in terms of traffic control equipment. A community cannot return to daily activities when its road system is not functional. Though aid from the federal government could be expected through FEMA and FHWA, these funds can take months to be received and require detailed accounting of reimbursable expenditures by local agencies.

In order to recover the damaged signs, signals, and lights, VDOT should decide on an adequate level of reserves in advance. Managing the required quantities of reserves for signs, signals and lights in preparation of a hurricane is a difficult task. One has to be able to find an appropriate level where there is a reasonable amount of reserves, while keeping costs low, and being able to contribute to an expeditious recovery after a hurricane.

Reserves have to be maintained at such level to allow for an initial recovery effort. Furthermore, months after a hurricane a well-chosen level of reserves will enable a steady recovery. Having an initial but substantial amount of reserves can permit enough time for production (sign shops) to supply the amounts of signs, signals and lights that are still required for the months ahead.

A decision whether to increase reserves prior to a hurricane affecting the area could be critical. The levels of reserves for the Tidewater region are determined largely according to patterns observed in previous years. VDOT does not currently increase levels of traffic equipment reserves during hurricane season.

Therefore, the research allows the highway agency to determine all the possible alternatives, which in turn allows a better decision to be made in managing reserves.