# Enhancement of Winter Maintenance Material Ordering and Inventory

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16. Abstract

Expenditures for winter maintenance materials total nearly $20 million annually. During an average winter ODOT uses approximately 666,000 tons of rock salt and has the capacity to store roughly 617,000 tons of material at various locations. Each year, each county in Ohio establishes a contract through ODOT with a salt vendor before the winter season and that vendor supplies all garages in the county for the entire season. In order to develop a systematic salt inventory management strategy that achieves the statewide goals for safety, this project developed ordering guidelines for each county that specifies when to order and how much to order based on an ($R$, $S$)-inventory guideline. These guidelines take into account the history of usage and deliveries in a county, as well as the monthly variation in usage. The inventory guidelines developed for the different areas of Ohio are based on a weather regression model for the major cities/counties in the state relating usage to weather. The guidelines were tested and refined using a computer simulation methodology. The resulting guidelines are compared to the current ODOT guidelines for inventory, as well as compared to the county storage capacities to develop recommendations. The project also developed design concepts for inventory monitoring to support effective ordering.

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# SI* (MODERN METRIC) CONVERSION FACTORS

## APPROXIMATE CONVERSIONS TO SI UNITS

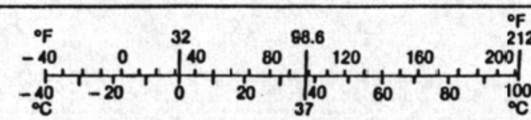
| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | 25.4 | millimetres | mm |
| ft | feet | 0.305 | metres | m |
| yd | yards | 0.914 | metres | m |
| mi | miles | 1.61 | kilometres | km |
| | | **AREA** | | |
| $in^2$ | square inches | 645.2 | millimetres squared | $mm^2$ |
| $ft^2$ | square feet | 0.093 | metres squared | $m^2$ |
| $yd^2$ | square yards | 0.836 | metres squared | $m^2$ |
| ac | acres | 0.405 | hectares | ha |
| $mi^2$ | square miles | 2.59 | kilometres squared | $km^2$ |
| | | **VOLUME** | | |
| fl oz | fluid ounces | 29.57 | millilitres | mL |
| gal | gallons | 3.785 | litres | L |
| $ft^3$ | cubic feet | 0.028 | metres cubed | $m^3$ |
| $yd^3$ | cubic yards | 0.765 | metres cubed | $m^3$ |

NOTE: Volumes greater than 1000 L shall be shown in $m^3$.

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **MASS** | | |
| oz | ounces | 28.35 | grams | g |
| lb | pounds | 0.454 | kilograms | kg |
| T | short tons (2000 lb) | 0.907 | megagrams | Mg |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5(F-32)/9 | Celcius temperature | °C |

## APPROXIMATE CONVERSIONS FROM SI UNITS

| Symbol | When You Know | Multiply By | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimetres | 0.039 | inches | in |
| m | metres | 3.28 | feet | ft |
| m | metres | 1.09 | yards | yd |
| km | kilometres | 0.621 | miles | mi |
| | | **AREA** | | |
| $mm^2$ | millimetres squared | 0.0016 | square inches | $in^2$ |
| $m^2$ | metres squared | 10.764 | square feet | $ft^2$ |
| ha | hectares | 2.47 | acres | ac |
| $km^2$ | kilometres squared | 0.386 | square miles | $mi^2$ |
| | | **VOLUME** | | |
| mL | millilitres | 0.034 | fluid ounces | fl oz |
| L | litres | 0.264 | gallons | gal |
| $m^3$ | metres cubed | 35.315 | cubic feet | $ft^3$ |
| $m^3$ | metres cubed | 1.308 | cubic yards | $yd^3$ |
| | | **MASS** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.205 | pounds | lb |
| Mg | megagrams | 1.102 | short tons (2000 lb) | T |
| | | **TEMPERATURE (exact)** | | |
| °C | Celcius temperature | 1.8C + 32 | Fahrenheit temperature | °F |




* SI is the symbol for the International System of Measurement

(Revised April 1989)

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## Problem Statement

Expenditures for winter maintenance materials total nearly $20 million annually. During an average winter ODOT uses approximately 666,000 tons of rock salt and has the capacity to store roughly 617,000 tons of material at various locations. Despite the enormous cost and magnitude of this particular element of winter maintenance, current systems in place for ordering, inventory management and storage requirements are not well defined or established. Current systems are the result of years of practical application and evolution and numerous problems occur that are directly related to the lack of detail, specifics and minimum requirements as related to these areas. Criteria for minimum storage capacity do not exist and stock pile storage requirements are minimal. Timely ordering issues pose frequent problems during peak usage periods and as a result, winter maintenance materials are frequently depleted during severe winter weather conditions. Guidelines, minimums and processes need to be reviewed for effectiveness and efficiency for controlling and maintaining these inventories.

Availability of winter maintenance materials is the foundation upon which successful winter maintenance operations are built. Maintaining high levels of service during and following winter storms has a critical impact on sustaining economic activity and ensuring public safety. This project investigated improved inventory management and procedures based on a study of usage of winter materials. The improved procedures incorporate uncertainties in demand and supply into new ordering guidelines used to replenish inventories. These guidelines are based on maintaining high levels of service at the lowest possible cost. Information collected from our literature review has helped leverage existing knowledge on inventory management and contract terms. The improved inventory control guidelines were tested using simulation to demonstrate their impact to project stakeholders. This simulation approach was driven by data from the material usage studies and the proposed inventory control guidelines.

Research Tasks from proposal:

1. Detailed literature search.
2. Study current operating practices for inventory.
3. Investigate contract terms and supplier relations.
4. Material usage and delivery study by geographical area.
5. Study best practices used by others.
6. Develop inventory control guidelines.
7. Develop recommendations for contract terms/supplier relations
8. Develop recommendations for procedures for tracking inventory.
9. Prepare final report and executive summary.

# 1. Introduction

Use of winter maintenance materials is critical to maintaining safe economic and social activity in the State of Ohio during the winter season. Each year, snow and ice storms create situations filled with danger to the public and potentially enormous economic cost. The rate of traffic accidents has been observed to increase by a factor of 100 during a winter storm [Knapp, et. al., 2000]. It is well known that during winter storms, the use of salt and other treatments has a large impact on safety. For example, one study found that the rate of accidents decreases by a factor of 4.5 times in the two hours after roads have been treated following a snowfall, and that the rate for injury accidents decreases by a factor of seven times [Kuemmel, 1992]. The economic impacts of prolonged road closures or delays to the clearing of roads are significant. It has been estimated that the effect per day of a snowfall "shut-down" in Ohio has a total economic impact of $281 million [Arnsler, 2004].

This chapter summarizes the background for the project, and gives an overview of some of the major findings that are detailed in the remainder of the report. We give examples of the major inventory guideline findings for an example Ohio county, and a high-level view of the regression methodology used to develop those findings as well as some insight into how they could be implemented. The following chapters contain more exhaustive detail on the methodologies used to develop the project findings, as well as enumerate the results for all counties. This chapter should serve as a complete overview of the project's findings, with enough detail to direct the reader to the appropriate succeeding sections based on his/her interest.

## 1.1. Background

When the seasons change in Ohio from spring and summer to the fall and winter the temperatures begin to drop and the precipitation changes from rain to snow and ice. When this occurs roads can become treacherous and to protect travelers from the dangers of snow and ice highway crews are out making roads safe for travel. If the roads become impassable the social and economic impacts are tremendous and cost the state of Ohio a significant amount of money each day the roads are dangerous to drive on. The most common way for highway crews to make roads passable is with the use of road salt. There are many methods to treat roads in a highway crew's arsenal such as grit, brines, and chemicals, but the major method is the use of road salt. County trucks that hold about 10-12 tons of salt each are sent out to spread salt on roads before, during, and after a storm to prevent ice and snow build up. It is crucial that the storage bins at the county garages do not run out of salt during the winter season.

The salt supply chain for the winter maintenance for the State of Ohio is summarized in Figure 1.1. Each year, each county establishes a contract through ODOT with a salt vendor before the winter season and that vendor supplies all garages in the county for the entire season. The supplier selects one of its stockpile locations that will supply the contracted county for the term of the contract. Only one vendor supplies a county, but many counties can be supplied by one vendor. The vendor/stockpile locations are stocked by the vendor's own mines or third party mines that transport the salt by rail or barge. The county garages are stocked by the vendor by transporting truckloads of salt from the vendor stockpiles to the storage bins at the county garage by contracted carriers. This process of stocking the salt bins for the winter season begins in the summer months and continues until a specified volume is reached in the county garages, usually before the start of winter weather. During the winter season as salt is used, salt is then reordered by the county based on an estimate of the amount that remains in the bins. When to order and how much to order varies from county to county and the ordering process is not at all a complete science. Some guidelines are provided by the Maintenance Administration Manual (2005), an internal Ohio Department of Transportation (ODOT) document that provides guidelines for the amount to be stocked over the year.

In order to develop a systematic salt inventory management strategy that achieves the statewide goals for safety, this project developed ordering guidelines for each county that specifies when to order and how much to order based on an $(R, S)$-inventory guideline. These guidelines take into account the history of usage and deliveries in a county. This guideline is valuable because it more closely matches the county inventories to the actual demand, which results in more efficient snow removal operations.

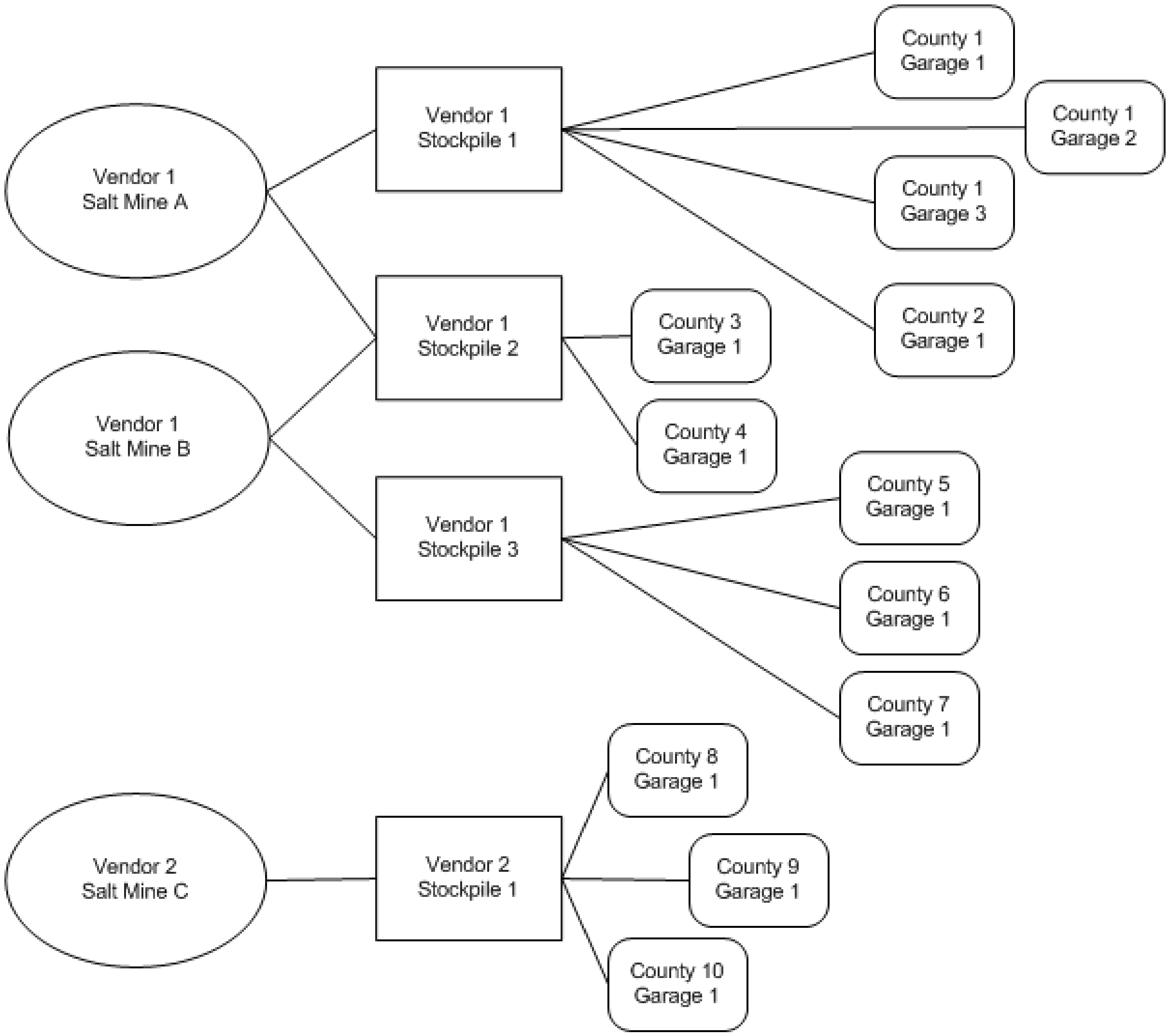


**Figure 1.1 - The Salt Supply Chain**

In the academic literature, there is a long history of studying inventory and materials management. These models describe the structure of ordering decisions in inventory management situations. The standard models [Nahmias, 1999] include:

1. "Economic Order Quantity" (EOQ) models: These models demonstrate the trade-off between fixed ordering costs, cost per unit of material, and the costs due to holding of inventory over time. The model describes the quantity of material that should be ordered each time inventory reaches zero. This order quantity minimizes a simplified model of average costs over time. Extensions of this model which are relevant to the winter materials setting is consideration of quantity discounts in the pricing of the materials [Schreibfeder, 1999]. The classic version of this model has been used for 100 years, but does not consider any variation or randomness in any of

the parameters over time. The extension of this model to problems with a fixed lead-time is straightforward, by shifting orders earlier in time by the amount of the lead-time.

2. Models with uncertainty in demand: The EOQ model can be extended to include random variation in the demand. This leads to the use of ($Q$, $r$) guidelines. The $Q$ is the order quantity. Sometimes $Q$ is referred to as the "cycle stock": It represents the average demand during the time between replenishment orders. The "safety stock" portion of inventory helps to buffer against the uncertainties in the system. For example, safety stock is needed for those occasions when actual usage exceeds forecasted demand. Safety stock also provides protection from shortages when the time it takes to receive a replenishment shipment exceeds the projected lead time. Orders are placed when the inventory level drops to the level $r$. Figure 1.2 shows a schematic drawing of the change in inventory over time.

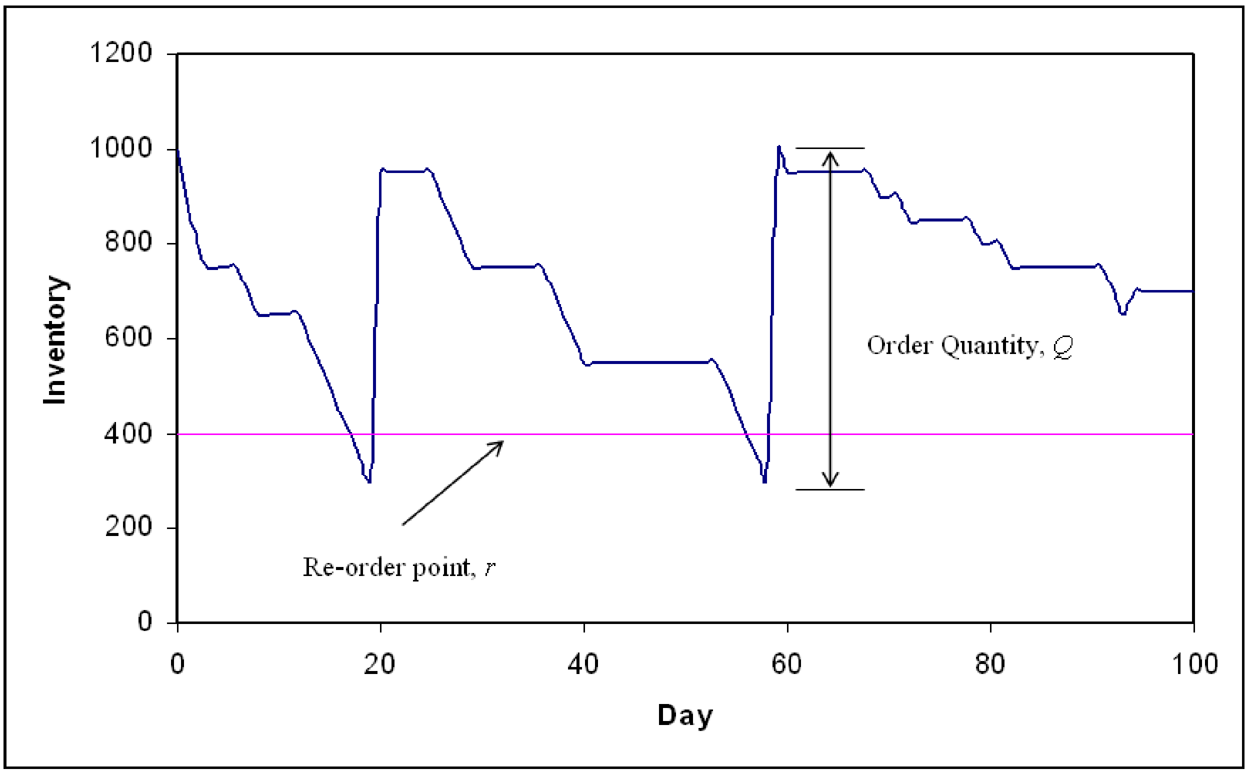


**Figure 1.2 - Schematic of Inventory Usage and Replacement**

The critical insight of these types of models is that in determining $r$ (re-order point) one must consider the statistical variation of demand during the delivery lead time. Simultaneous computation of $Q$ and $r$ to minimize the average cost over time is the result of this approach. The ($Q$, $r$)- type guideline assumes that inventory orders can be placed at any time. The "newsvendor" type models are a related class that assumes that inventory can only be ordered on a periodic basis (for example, once per week). Similar "order-quantity" and "safety stock" results are available for this type of model. In this context, the guidelines are called (*S*, *s*) guidelines [Eppen, Schrage, 1981]. For each of these approaches, a description of the range of possible demands over some base time period is critical to developing the order quantities and re-order points. These descriptions are statistical in nature, rather than precise forecasts, and should be based on historical information.

## 1.2. Project Overview

In the salt inventory context, based on our observation of actual practice, order quantities should be driven less by cost considerations, and more by the desired *frequency of orders*. The frequency of orders comes into play because if *Q* represents, for example, the 1 week average demand for a location, then orders will have to be placed, on average, about once per week.

A recent paper [Roelants, 2002] is closely related to the work on this project. It describes salt inventory management guidelines based on the (*Q*, *r*) model developed in Belgium that focus on matching salt inventories to actual demand during the winter months. Using a guideline that considered safety stocks explicitly, they used simulated and historical salt demands to determine salt order amounts and inventory levels to trigger orders. The paper claims that order quantities and safety stock levels must vary as the winter storm season progresses, to reflect variation in the underlying cost and demand parameters. In addition, the approaching end of the winter season must be taken into account when making inventory stocking decisions. It is important to consider the expected demand during the remainder of the season, as well as considering potential opportunities to purchase materials from suppliers at discounted costs.

This project developed (*R*, *S*)-inventory guidelines that takes into account demand amounts (either historical usage or predictions) to calculate reorder points and stock target levels. These guidelines were developed using a methodology based on by Roelants and Muyldermans (2002) that describes in detail how an (*R*, *S*)-inventory guideline was developed for a county in Belgium. The paper compares calculating the (*R*, *S*)-inventory guideline parameters using the historical salt usage data and the development of a weather regression model to calculate predictions. In an (*R*, *S*) guideline, the reorder point *S* answers the question of "when to order" and the stock target level answers the question of "how much to order".

Reorder points are computed by taking into account the mean usage during the supplier delivery lead time and then adding a safety stock which is found by multiplying the standard deviation of the usage during the lead time by a safety factor. The safety stock is additional inventory held in anticipation of unexpected demand. The safety factor used in the development of the Belgium (*R*, *S*)-inventory guideline is 99.8% which equates to a safety factor of 2.88 (for normally distributed demand). The safety stock is added to the expected usage for the week to determine the reorder point. Adding the reorder point to the expected usage for a week determines the stock target level for a weekly ordering process. The stock target level, *S*, determines the amount of the order. When the starting inventory, *I*, drops below the reorder point, *R*, an order of size $S - I$ is placed.

In the Belgian project, predictions of usage based on a weather regression model were more effective when used to develop the (*R*, *S*)-inventory guideline, rather than using historical demand directly. Thus the inventory guideline developed for the different areas of Ohio are based on a weather regression model for the major cities/counties in the state relating usage to weather. An (*R*, *S*)-inventory guideline was developed for all counties, even though only the largest cities have weather data available. All demand data for the models were accumulated on a weekly basis and these numbers were matched up with the corresponding weekly accumulated weather variables. A unique set of (*R*, *S*) values was developed for each month for each county based on a lead time of one week. Thus the reorder point and inventory target levels are computed based on weekly amounts with the values changing each month. The regions of Ohio are assigned a weather regression model from one of the major cities using the information in Figure 1.3 for average snowfall (ODOT website, 2006).

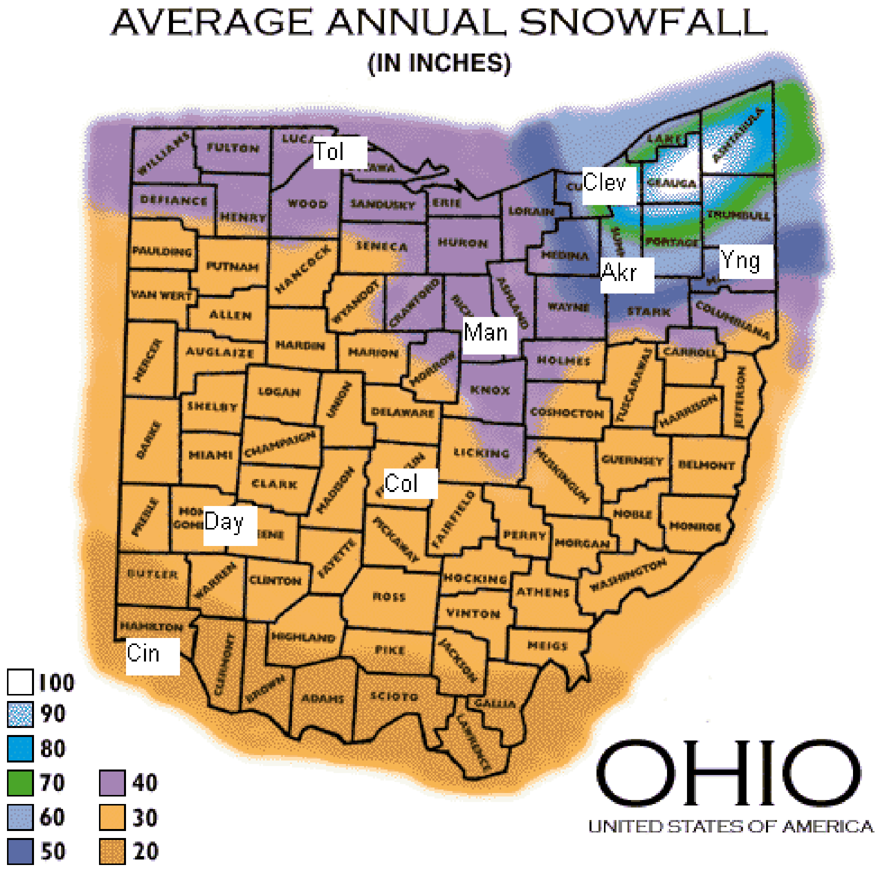


**Figure 1.3 - Map of Ohio Indicating Counties and Major Cities**

Figure 1.3 shows that average snowfall amounts vary widely across the state, and cause wide variation in the usage of salt. This is because of significant differences in the weather patterns and miles of roadway that are a function of the size of the cities in the area. The urban areas in northern Ohio, especially in the "lake effect" region along the shores of Lake Erie, see significantly more snow and use more salt than areas in other parts of the state. Areas in central Ohio historically use more salt than southern parts of Ohio along the Ohio River, and so on. Because of this, a single (*R*, *S*)-inventory guideline for the entire state will not be effective and it is necessary to develop different (*R*, *S*)-guideline parameters for each of the counties. Chapter 4 details development of salt usage models tailored for each region of the state based on weather data. The models use weather data from the major city located within each region.

As stated by Roelants and Muyldermans (2002) the (*R*, *S*)-inventory guideline is more effective when it uses predictions developed from a multi-variable weather regression model. In that model demand salt amounts were matched up with weather variables from the same time period and then a linear regression model was fit. Figure 1.4 diagrams the process of calculating the (*R*, *S*)-inventory guideline.

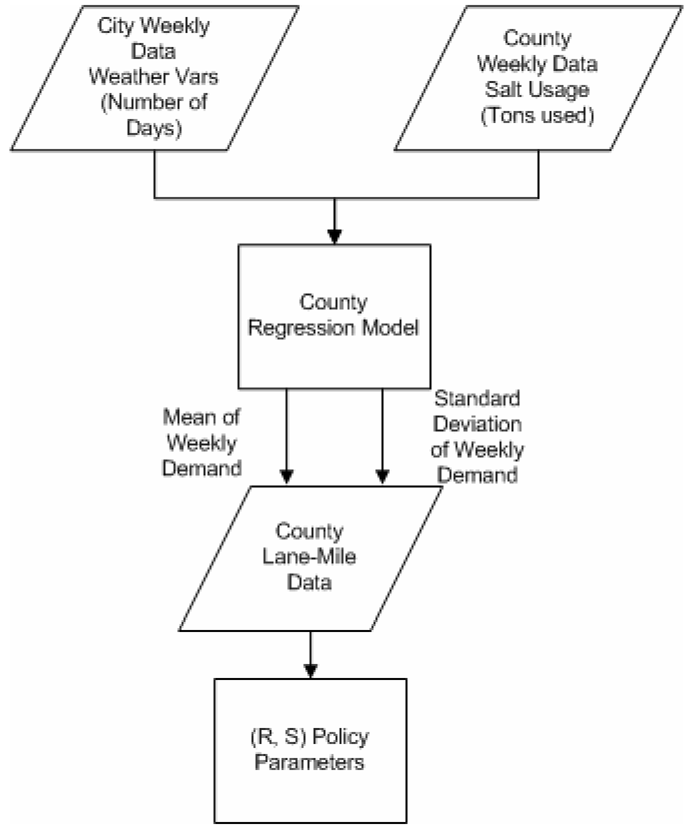


**Figure 1.4 - (*R*, *S*) Inventory Guideline Development Process**

The weekly predictions from the regression model are used to compute statistics of usage for the (*R*, *S*)-inventory guideline. The regression model was developed by finding the most significant weather variables characteristic of salt usage. Because the paper written by Roelants and Muyldermans does not clearly describe the details of weather variables used, another paper written by McCullouch, Belter, Konieczny, and McClellan (2004) was used to establish the weather variables used in the model. The paper compared different weather indices used around the United States and was developed for the State of Indiana. The use of these results is important because of the similarity of the weather in Indiana to Ohio, where there are high amounts of snowfall in some areas and extremely low snowfall in other areas. Starting with the weather variables suggested in the McCullouch et al. (2004) paper an Excel spreadsheet was set up to import weather files (NOAA website, 2006) to examine some of the weather variables. Table 1.1 - Weather Variables displays the weather variables considered for weather regression models for each county. The most significant variables were found through a systematic procedure of adding/removing variables from the regression model. The decision to add or remove a variable was based on the impact on the $R^2$, $R^2$ adjusted, and mean squared error of the model.

**Table 1.1 - Weather Variables**

| Events | Symbols | Definitions |
|---|---|---|
| Snow | Sn | Amount of Snowfall > 0 in.<br>Amount of Snowfall > 0.001 in. |
| Days of Snow | DSn | Number of days of Snowfall > 0 in.<br>Number of days of Snowfall > 0.001 in. |
| Freezing Rain | FzR | Number of days with Freezing Rain/Freezing Drizzle |
| Blowing Snow | BSn | Number of days with Blowing Snow |
| Snow Cover | SnC | Number of days of ground snow cover > 0 in.<br>Number of days of ground snow cover > .001in. |
| Minimum Temperature | MinT | Number of days with minimum temperature < 30°<br>Number of days with minimum temperature < 32° |
| Maximum Temperature | MaxT | Number of days with maximum temperature < 30°<br>Number of days with maximum temperature < 32° |
| Average Temperature | AveT | Number of days with average temperature < 30°<br>Number of days with average temperature < 32° |

As an example, the variables included in the final monthly model for Cuyahoga County are summarized in Table 1.2 - Cuyahoga County weather variables used for the regression model. Below the table, are the final equations relating weather variables to predicted weekly salt usage for Cuyahoga County for each month.

**Table 1.2 - Cuyahoga County weather variables used for the regression model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >.001 | >.001 | | | | <30 | <30 | <30 | 0.991 | 0.989 | 10200 |
| Dec. | >.001 | >.001 | X | | >.001 | | | | 0.921 | 0.911 | 561000 |
| Jan. | >.001 | | X | | | | | <30 | 0.951 | 0.944 | 461000 |
| Feb. | >.001 | >.001 | X | X | | <30 | | <30 | 0.937 | 0.919 | 200000 |
| Mar. | >.001 | >.001 | | X | | | | <32 | 0.927 | 0.914 | 277000 |

$$\text{Cleveland}_{nov.} = 22.001 + 283.73 * \text{Sn} + 129.63 * \text{DSn} - 997.74 * \text{MaxT} - 50.077 * \text{MinT} + 1255.4 * \text{AveT}$$

$$\text{Cleveland}_{dec.} = -287.88 + 255.94 * \text{Sn} + 357.68 * \text{DSn} + 761.25 * \text{FzR} + 300.87 * \text{SnC}$$

$$\text{Cleveland}_{jan.} = -481.49 + 472.60 * \text{Sn} + 1253.0 * \text{FzR} + 238.55 * \text{AveT}$$

$$\text{Cleveland}_{feb.} = -63.303 + 256.88 * \text{Sn} + 191.81 * \text{DSn} + 355.09 * \text{FzR} + 669.02 * \text{BSn} - 182.39 * \text{MaxT} + 139.69 * \text{AveT}$$

$$\text{Cleveland}_{mar.} = -118.80 + 197.75 * \text{Sn} + 347.23 * \text{DSn} + 559.45 * \text{BSn} - 148.97 * \text{SnC} + 223.73 * \text{AveT}$$

It was apparent from the results of the Roelants and Muyldermans paper that a significant relationship exists between weather variables and salt usage. This was examined by graphing salt usage against different weather variables. For example, Figure 1.5 shows that as weekly snowfall increases in Cuyahoga County that salt usage also increases. As other variables are added to the regression, more of the variability is explained by the model.

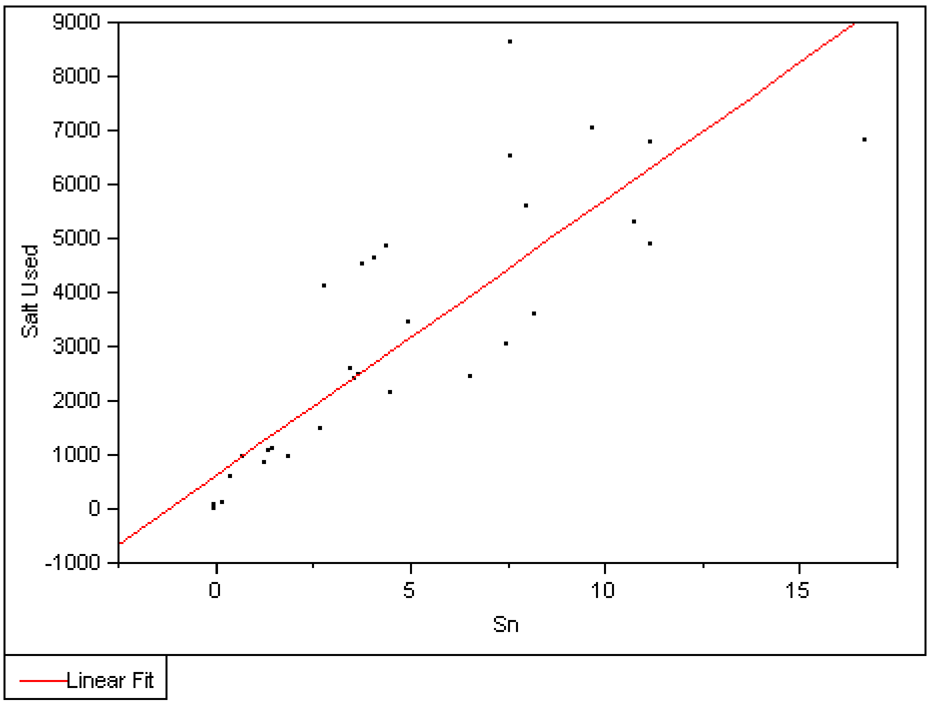


**Figure 1.5 - Salt usage in Cuyahoga vs snowfall (inches) in January**

Through simulation the ($R$, $S$)-inventory guideline parameters were examined to test the effectiveness of implementing the guideline. Figure 1.6 diagrams the simulation model developed to support this test. It begins with actual usage data and the ($R$, $S$) inventory parameters and results in inventory levels and streams of orders.

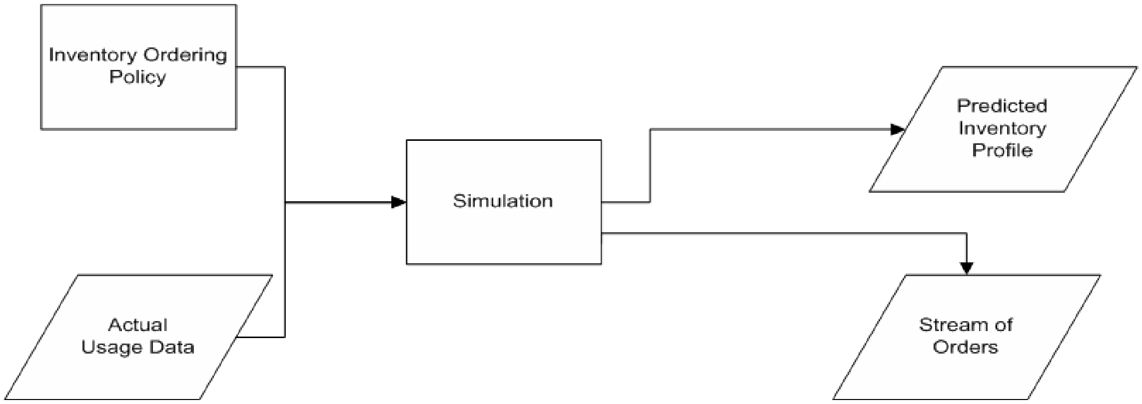


**Figure 1.6 - Diagram of the simulation model inputs and outputs**

To accurately model reality the simulation utilized actual data provided by ODOT on salt received for each county. The (*R*, *S*)-inventory guidelines were used to simulate when to reorder and the order amounts. Because salt deliveries occur over time in reality a simple model of deliveries was also developed. This occurs because a large salt order is subdivided into a number of truck deliveries that can take place over hours or days. This model subdivided large orders into daily deliveries to the county inventories based on the amount of salt each garage can receive in one day. Running this model using beginning-of-season inventory levels, from ODOT historical data, the average inventories and the number and pattern of orders can be compared to actual historical numbers. The inventory levels based on actual usage were also computed by using a similar simulation model and running it with actual received, used and beginning inventory numbers.

The development and analysis of the model served two purposes. One purpose was to study the effectiveness of the new guidelines. During the testing process, the simulation was also used to establish several parameters in the implementation of the guidelines. One parameter is the best starting inventories for garages at the start of the winter season. Because inventories at the end of the winter season are similar to the target levels for March, and these inventory levels are higher than the November target level, a target level for November should be investigated. It was found through simulation and the evaluation of output data that setting the beginning inventories to that of January's target level minimizes the number of orders and the number of stockouts by increasing average inventories slightly over other alternatives. This guideline also mimics the practice within ODOT to "stock up" on inventory early in the winter season as a conservative way to avoid problems due to supply disruptions.

Another purpose served by the simulation was determining when to switch from one month's guideline parameters to the following months. This turns out to be especially important when the following months target level is higher. Because of the lead time for deliveries, switching guidelines on the 1st of a month might delay reaching the target level up to a week into the month. This leads to a higher risk of shortages during these time periods. This dilemma was answered by beginning to implement December and January's guideline seven days before the first day of these months. This results in county inventories beginning the month closer to the appropriate target levels.

It was found through the simulation of Cuyahoga and Lucas counties that overall average inventories were increased slightly, but that in most cases the number of orders decreased. The simulation was instrumental in determining the effectiveness of the inventory guideline; something not studied in the Roelants and Muyldermans (2002) paper. An example of the result of a simulation run is shown in Figure 1.7, where the inventory levels using the new guideline as well the actual inventories are graphed for Cuyahoga County in winter 2005. These yearly results were compared to draw conclusions on average inventory levels, order patterns and shortage risks.

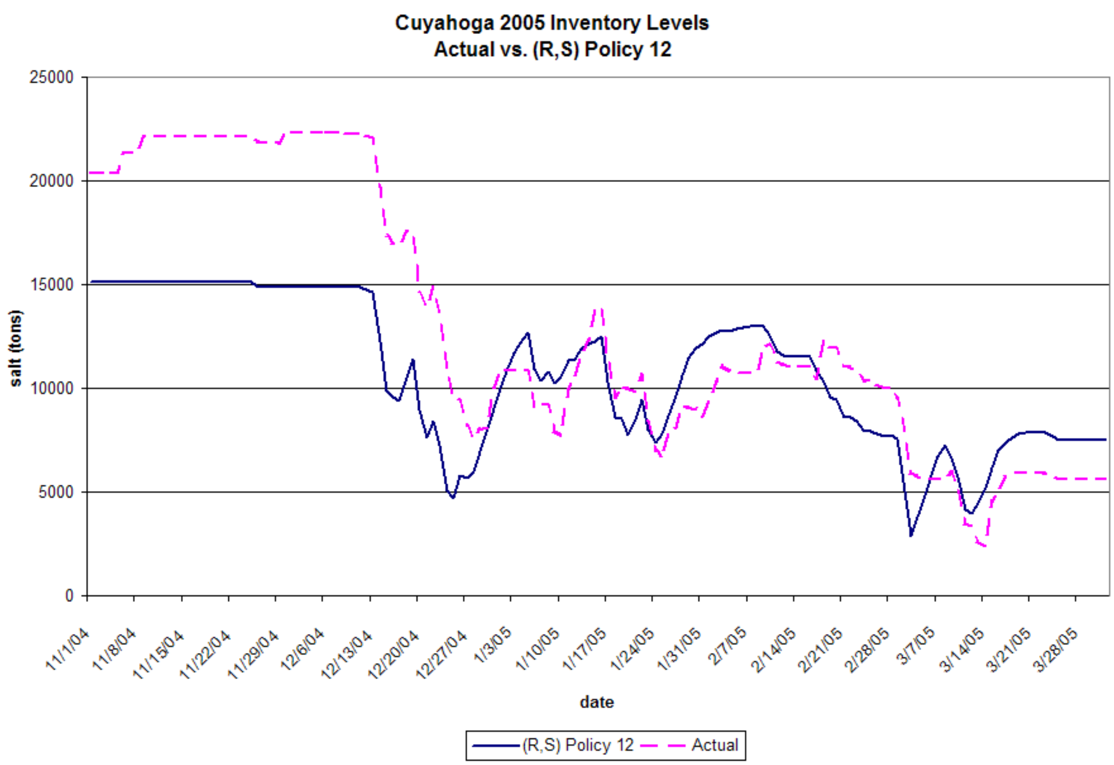


**Figure 1.7 - Cuyahoga actual inventories vs. inventories under (*R*, *S*) guideline 12**

Through the different simulation runs it was found that as the beginning inventories were increased the average inventory levels increase, but the number of orders placed decrease. In working with the guidelines and varying the ordering parameters, the simulations identified some historical situations where the guideline parameter settings are critical to maintaining adequate stocks. If guideline parameters are not chosen carefully, our simulation tests showed that in some historical situations, when combined with simulated random resupply delays, stockouts can occur. For example, when tested against the winter of 1999 data, with random supply delays well beyond a nominal 7 day delivery lead-time, some of the guidelines we tested showed brief stockouts. Guidelines with stockout problems in realistic situations were eliminated from consideration. From conversations with ODOT representatives we learned 1999 was an exceptional bad winter due to high usage of salt in a short period of time. Other than the winter of 1999 all guidelines perform well with guideline 12 being used due to its lower order numbers and higher minimum inventory levels, which also helps protect from shortages. Guideline 12 is a guideline where we set the beginning inventory levels to January's stock target level and beginning the (*R*, *S*)-inventory guideline parameters of December and January 7 days into the previous month.

Through the development of the (*R*, *S*)-inventory guideline and the subsequent simulation analysis we conclude that:

1. Beginning inventories of each winter season should be set to the stock target level of January.
2. The (*R*, *S*) parameters for the months of December and January should be used 7 days early at the end of the preceding month. December guidelines will begin November 24th and January guideline should begin December 25th. The implementation of the guidelines for the months of February and March will begin on the 1st.
3. Counties without relevant weather data may use historical usage data to formulate the (*R*, *S*)-inventory guideline.
4. Counties without weather data can utilize a nearby larger county's weather model to calculate their own (*R*, *S*)-inventory guideline while taking into account mileage differences.

## 1.3. Report Summary

This project developed an (*R*, *S*)-inventory guideline for use in every Ohio county. The guideline systematically identifies at what point a county manager should order salt and how much should be ordered. Through the development of a weather regression model, predictions were developed to more accurately support the inventory guideline parameters that balance shortage risk and inventory lost. To examine the efficiency and effectiveness of the model a simulation was developed that closely resembles the actual system at an appropriate level of detail. All data pertaining to usage, received, and beginning amounts were provided by ODOT through an internal cd-rom entitled Winter Maintenance Material

Ordering & Inventory (2006). The development of the weather regression model used data from the National Oceanic Atmospheric and Administration web site, collected by National Climatic data center.

The rest of this report is organized as follows: Chapter 2 presents a review of literature in the area of inventory guidelines, supply chain management and their application to bulk commodities. Chapter 3 reviews the background on the literature that supports the (R, S) inventory guideline in particular, the weather severity index literature, and supply chain management as it has been applied in the area of bulk commodities. Chapter 4 presents the regression model relating salt used to weather variables. This chapter also details the regression models developed for the 7 major weather zones in Ohio. Chapter 5 presents the (*R*, *S*)-inventory guidelines developed using the weather model for each Ohio weather zone. Chapter 6 presents results and refinement of the inventory guidelines through simulation tested against actual usage from ODOT databases. Chapter 7 summarizes the analysis of the county and vendor capacities in light of the developed inventory control guidelines. Chapter 8 presents conclusions and some suggestions for implementation and future work.

## 1.4. Inventory Guideline Summary

One of the major results of the detailed analysis in the succeeding chapters of this report is the determination of the (*R*, *S*) inventory parameters for each county in Ohio. These parameters are summarized succinctly in Figure 1.8, which lists the final results for each county, arranged by district. Figure 1.8 also shows the 10 day maximum usage for each county, as determined for data through the 2007-08 winter season. Finally Figure 1.8 shows the numerical difference between the proposed inventory targets (*S*) and the 10 day maximum usage. In cases where this difference is large, the recommendations from our analysis differs significantly from the current ODOT practice.

To operate using the (*R*, *S*) guideline parameters, the following logic is used:

> When the total of *on_hand inventory* + *orders_in_transit* drops below the level *R*, an order for *S* - (*on-hand inventory* +*orders_in_transit*) is placed.

Notice that for the (*R*, *S*) guideline to operate correctly, both the on-hand inventory (shown in the equation as the *on_hand inventory*) and the total volume of orders in transit (shown in the equation as the *orders_in_transit*) must be tracked, at least approximately. Orders in transit for a county represents the amount of salt that is on order, but has not yet been delivered.

Figure 1.8 includes the values for *R* (re-order point) and *S* (inventory target) for each county. It also lists the 10 day maximum usage for each county, as of January of 2009. The comparison of the values is instructive, since current ODOT stocking plans are based on the 10 day maximum usage. (Also, note that a comparison of the inventory targets from this project and the county storage capacities is detailed in Chapter 7.)

For the following counties, the 10 day maximum usage is at least 1000 tons larger than the suggested inventory targets: Wood, Preble, Muskingum, and Butler. For these counties, our analysis indicates that significantly less than the 10-day max usage may be sufficient as an inventory target. A deeper analysis to see what fundamentally leads to the lower value in our approach is warranted for these counties. By using the proposed guideline, it may be possible to reduce the inventories significantly in these counties, given that the 10-day maximum is the current guideline, without a negative service level impact. In general, any consideration of decreasing inventory levels must be taken with great care.

For the following counties, the 10 day maximum usage is between 500 tons and 1000 tons larger than the suggested inventory targets: Montgomery, Fairfield, Licking, Hancock, Monroe, Auglaize, Stark, Lucas, Holmes, Franklin, Shelby, Columbiana and Ashland. A deeper analysis to see what fundamentally leads to the lower value in our approach is warranted for these counties. By using the proposed guideline, it may be possible to moderately reduce the inventories in these counties, given that the 10-day maximum is the current guideline, without a negative service level impact. In general, any consideration of decreasing inventory levels must be taken with great care.

For the following counties, the 10 day maximum usage is between 500 and 1000 tons smaller than the suggested inventory targets: Medina, Madison, Union, Richland and Tuscarawas. For these counties our analysis indicates that considering a moderate increase in the inventory levels is necessary to maintain an adequate level of service.

For the following counties, the 10 day maximum usage is at least 1000 tons smaller than the suggested inventory targets: Ashtabula, Geauga and Cuyahoga. For these counties, our analysis indicates that significantly more than the 10-day max usage may be necessary as an inventory target. It is likely that increasing the inventories in these counties can improve the level of service. It is worth noting that all three of these counties have among the highest overall usage in the state. If deliveries from the vendors to these counties are more reliable than to other counties because of the regularity of delivery and the volume of orders, then the 10 day max may be acceptable as an inventory target.

In all of the remaining county studies not mentioned above, the suggested inventory target was within 500 tons of the 10 day maximum usage. We recommend that no change be made in the inventory guideline for these counties. Of course, the suggested inventory targets and re-order points from the project analysis can be used to guide ordering for all counties. The difference between the 10 day maximum usage guideline and the proposed guidelines in these cases is relatively small. In these cases the recommendation from the two methodologies are not significantly different.

The following chapters detail the methodology and process that was used to develop these and other recommendations.

| DISTRICT | COUNTY | Historical 10 Day Max Usage (tons) | January ReOrder Point | January Inventory Targets (tons) | Difference = 10_Day_Max - January_Target |
|---|---|---|---|---|---|
| 1 | Allen | 2,368 | 1500 | 1910 | 458 |
| 1 | Defiance | 1,538 | 1050 | 1340 | 198 |
| 1 | Hancock | 2,972 | 1870 | 2410 | 562 |
| 1 | Hardin | 1,825 | 1087 | 1395 | 430 |
| 1 | Paulding | 1,306 | 995 | 1260 | 46 |
| 1 | Putnam | 1,485 | 1060 | 1350 | 135 |
| 1 | Van Wert | 2,020 | 1500 | 1920 | 100 |
| 1 | Wyandot | 1,901 | 1410 | 1790 | 111 |
| 2 | Fulton | 1364 | 911 | 1180 | 184 |
| 2 | Henry | 1,682 | 1160 | 1430 | 252 |
| 2 | Lucas | 2,513 | 1380 | 1700 | 813 |
| 2 | Ottawa | 1,954 | 1440 | 1860 | 94 |
| 2 | Sandusky | 2,354 | 1580 | 2010 | 344 |
| 2 | Seneca | 2,665 | 1720 | 2200 | 465 |
| 2 | Wiliams | 2,152 | 1590 | 2050 | 102 |
| 2 | Wood | 6,959 | 3940 | 5030 | 1929 |
| 3 | Ashland | 4769 | 2880 | 3780 | 989 |
| 3 | Crawford | 2,505 | 1940 | 2550 | (45) |
| 3 | Erie | 2,272 | 1970 | 2560 | (288) |
| 3 | Huron | 2,600 | 2230 | 2910 | (310) |
| 3 | Lorain | 3,687 | 2500 | 3270 | 417 |
| 3 | Medina | 5,189 | 4510 | 5890 | (701) |
| 3 | Richland | 2,927 | 2620 | 3470 | (543) |
| 3 | Wayne | 2,076 | 1260 | 1660 | 416 |
| 4 | Stark | 6853 | 4790 | 6180 | 673 |
| 4 | Mahoning | 8,341 | 6150 | 8060 | 281 |
| 4 | Portage | 6,124 | 4800 | 6210 | (86) |
| 4 | Summit | 6,174 | 4830 | 6410 | (236) |
| 4 | Trumbull | 7,856 | 6340 | 8220 | (364) |
| 4 | Ashtabula | 11,045 | 11200 | 14900 | (3855) |
| 5 | Muskingum | 4870 | 3030 | 3820 | 1050 |
| 5 | Fairfield | 3,309 | 2140 | 2770 | 539 |
| 5 | Licking | 3,099 | 2010 | 2560 | 539 |
| 5 | Knox | 2,630 | 1910 | 2430 | 200 |
| 5 | Perry | 2,441 | 1810 | 2340 | 101 |
| 5 | Coshocton | 2,497 | 1900 | 2410 | 87 |
| 5 | Guernsey | 3,261 | 2720 | 3540 | (279) |
| 6 | Franklin | 10038 | 7150 | 9110 | 928 |
| 6 | Delaware | 2,872 | 2120 | 2720 | 152 |
| 6 | Pickaway | 1,631 | 1130 | 1480 | 151 |
| 6 | Marion | 2,311 | 1690 | 2210 | 101 |
| 6 | Morrow | 2,692 | 2300 | 2970 | (278) |
| 6 | Fayette | 2,651 | 2300 | 2940 | (289) |
| 6 | Union | 2,583 | 2420 | 3140 | (557) |
| 6 | Madison | 2,748 | 2550 | 3330 | (582) |

**Figure 1.8 - Final (R,S) Guideline Parameters with Comparison to 10-day Maximum Historical Usage**

| DISTRICT | COUNTY | Historical 10 Day Max Usage (tons) | January ReOrder Point | January Inventory Targets (tons) | Difference = 10_Day_Max - January_Target |
|---|---|---|---|---|---|
| 7 | Shelby | 1998 | 827 | 1060 | 938 |
| 7 | Auglaize | 1,940 | 1030 | 1290 | 650 |
| 7 | Montgomery | 2,656 | 1760 | 2140 | 516 |
| 7 | Logan | 2,450 | 1530 | 1960 | 490 |
| 7 | Miami | 2,310 | 1440 | 1830 | 480 |
| 7 | Champaign | 2,006 | 1210 | 1550 | 456 |
| 7 | Clark | 2,408 | 1640 | 2050 | 358 |
| 7 | Mercer | 1,547 | 971 | 1220 | 327 |
| 7 | Darke | 1930 | 1290 | 1630 | 300 |
| 8 | Preble | 3946 | 2270 | 2890 | 1056 |
| 8 | Butler | 2,785 | 1370 | 1760 | 1025 |
| 8 | Clermont | 3,591 | 2490 | 3180 | 411 |
| 8 | Warren | 2,939 | 2010 | 2550 | 389 |
| 8 | Hamilton | 5,020 | 3770 | 4780 | 240 |
| 8 | Clinton | 3,307 | 2550 | 3280 | 27 |
| 8 | Greene | 3,021 | 2460 | 3150 | (129) |
| 9 | Adams | 2188 | 1560 | 1970 | 218 |
| 9 | Brown | 2285 | 1460 | 1850 | 435 |
| 9 | Highland | 1,551 | 1460 | 1860 | (309) |
| 9 | Jackson | 1,594 | 1370 | 1740 | (146) |
| 9 | Lawrence | 1,383 | 942 | 1190 | 193 |
| 9 | Pike | 1,417 | 1010 | 1280 | 137 |
| 9 | Ross | 2,544 | 2110 | 2680 | (136) |
| 9 | Scioto | 1,054 | 925 | 1170 | (116) |
| 10 | Athens | 1556 | 1510 | 1950 | (394) |
| 10 | Gallia | 1,180 | 872 | 1100 | 80 |
| 10 | Hocking | 1,751 | 1440 | 1900 | (149) |
| 10 | Meigs | 1,080 | 805 | 1030 | 50 |
| 10 | Monroe | 2,086 | 1150 | 1480 | 606 |
| 10 | Morgan | 1,441 | 1380 | 1800 | (359) |
| 10 | Noble | 2,394 | 2120 | 2730 | (336) |
| 10 | Vinton | 1,463 | 1310 | 1690 | (227) |
| 10 | Washington | 3,200 | 2430 | 3180 | 20 |
| 11 | Columbiana | 4,312 | 2510 | 3330 | 982 |
| 11 | Holmes | 2,745 | 1460 | 1860 | 885 |
| 11 | Carroll | 2,185 | 1290 | 1700 | 485 |
| 11 | Belmont | 4,501 | 3160 | 4130 | 371 |
| 11 | Jefferson | 3,193 | 2220 | 2920 | 273 |
| 11 | Harrison | 2,512 | 1780 | 2310 | 202 |
| 11 | Tuscarawas | 2675 | 2380 | 3180 | (505) |
| 12 | Lake | 5,246 | 4220 | 5480 | (234) |
| 12 | Cuyahoga | 14,258 | 11800 | 15300 | (1042) |
| 12 | Geauga | 6372 | 6100 | 8100 | (1728) |

**Figure 1.8 Final (R,S) Guideline Parameters with Comparison to 10-day Maximum Historical Usage (continued)**

# 2. Literature Review

Our research of existing literature identified 3 background areas of knowledge that supported the findings of the project:

1. Literature on inventory management
2. Literature and products in supply chain planning and execution
3. Knowledge from the winter maintenance professional groups, DOT's and materials suppliers

## 2.1. Inventory Management Literature

The material for this section consists mainly of the theory of inventory management from the academic literature. There has been very limited published material on the use of inventory management strategies for winter maintenance materials. The general principles from this section are applicable across the universe of inventory management problems.

In the academic literature, there is a long history of studying inventory and materials management. These models describe the structure of ordering decisions in inventory management situations. The standard models [Nahmias, 2001] include:

1. "Economic Order Quantity" (EOQ) models: These models demonstrate the trade-off between fixed ordering costs, cost per unit of material, and the costs due to holding of inventory over time. The model describes the quantity of material that should be ordered each time inventory reaches zero. This order quantity minimizes a simplified model of average costs over time. An extension of this model considers quantity discounts in the pricing of the materials [Schreibfeder, 1999]. The classic version of this model has been used for 100 years, but does not consider any variation or randomness in any of the parameters over time. The extension of this model to problems with a fixed lead-time is straightforward.

2. Models with uncertainty in demand: The EOQ model can be extended to include random variation in the demand. This leads to the use of ($Q$, $r$) guidelines. The $Q$ is the order quantity. Sometimes $Q$ is referred to as the "cycle stock": It represents the average demand during the time between replenishment orders. The "safety stock" portion of inventory helps to buffer against the uncertainties in the system. For example, safety stock is needed for those occasions when actual usage exceeds forecasted demand. Safety stock also provides protection from shortages when the time it takes to receive a replenishment shipment exceeds the projected lead time. In a ($Q$, $r$) guideline, orders are placed when the inventory level drops to the level $r$. Figure 2.1 shows a schematic drawing of the change in inventory over time. The critical insight of these types of

models is that in determining *r* (re-order point) one must consider the statistical distribution of demand *during the delivery lead time*. Simultaneous computation of *Q* and *r* to minimize the average cost over time is the result of this approach. The (*Q*, *r*)-type guideline assumes that inventory orders can be placed at any time.

Alternatively, in the "newsvendor" type models it is assumed that stock can only be ordered on a periodic basis (for example, once per week at a fixed time). Similar to the (*Q*, *r*)-type models, "order-quantity" and "safety stock" results are available for this type of model. For the newsvendor (or "periodic review") models of inventory ordering, the guidelines are called (*S*, *s*) guidelines [Eppen, Schrage, 1981]. For each of these approaches, a description of the range of possible demands over some base time period is critical to developing the order quantities and re-order points. These descriptions are statistical in nature, rather than precise forecasts, and should be based on historical information.

3. Deterministic models with time varying parameters: These models are often called "network flow" models based on the procedures used to solve them optimally. They consider the case where all of the parameters in the model can change on a periodic basis (say, weekly). This includes the cost parameters (per-unit purchase, holding, and fixed ordering cost) and the demands. A limitation of this approach is that all the parameters and demands are assumed to be known in advance for the entire decision horizon. Because of this assumption, these models are not appropriate for the winter maintenance materials ordering problem.

Some important parameters in the use of these models are:

- cost of storage per year per ton of material
- cost of purchase per ton of material, as well as fixed costs for an order of material
- data on usage over time (not just the mean, but some measure of variability as well)
- storage capacities
- re-supply lead times

The cost data is used to support the order quantity, *Q*, which is closely related to the order frequency [Nahmias, 2001].

- $Q = \sqrt{\frac{2AD}{h}}$, where $A$ = fixed cost of placing an order, $D$ = yearly rate of demand, $h$ = inventory holding cost per ton per year

When the order quantity is *Q*, and the average demand rate is *D*, then the order frequency will be one order every $Q/D$ time units. In practice, in situations where the cost parameters are not known precisely, order quantities may be based on storage capacities, or desired order frequencies. For example, if it is desirable to order once per week, then the order quantity can be based on one week of average demand.

The cost data can also be used to estimate an "optimal" level of service. From the inventory perspective, the level of service is typically defined as the fraction of periods where demand is satisfied from stock, without a shortage. It can also be defined as the proportion of total demand that is satisfied from stock, without a shortage. In the models, determining the optimal level of service requires knowledge (or an estimate) of the cost of shortage, which is typically difficult to obtain. Alternatively, the desired level of service can be based on expert opinion or industry standards. This is more often the approach taken in practice to determine the appropriate level of service.

For example, the most direct result of these models is to determine the reorder point, *r*, as follows [Nahmias, 2001]:

- $r = \theta + z\sigma$, where $\theta$ = mean demand during the delivery lead-time, $\sigma$ = standard deviation of demand during the delivery lead time, and $z$ = a factor determined by the desired level of service.

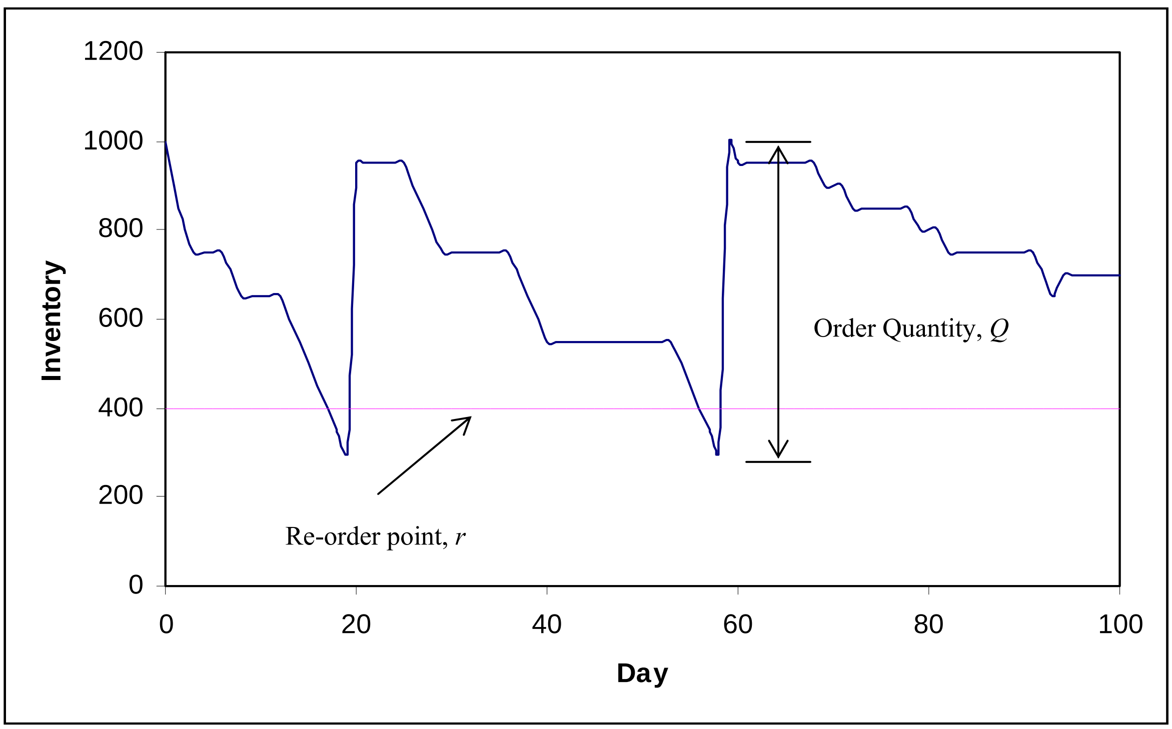


**Figure 2.1 - Schematic of inventory usage and replenishment**

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A recent paper [Roelants, 2002] is closely related to the work on this project. It describes salt inventory management guidelines based on the ($Q$, $r$) model developed in Belgium that focus on matching salt inventories to actual demand during the winter months. Using a guideline that considered safety stocks explicitly, they used simulated and historical salt demands to determine salt order amounts and inventory levels to trigger orders. The paper claims that order quantities and safety stock levels must vary as the winter storm season progresses, to reflect variation in the underlying cost and demand parameters. In addition, the approaching end of the winter season must be taken into account when making inventory stocking decisions. It is important to consider the expected demand during the remainder of the season, as well as considering potential opportunities to purchase materials from suppliers at discounted costs.

The PI's work in the area of inventory management with supply and demand uncertainty is also of relevance [Ciarallo,1994], [Ciarallo, 2000]. During heavy demand periods, supply can become uncertain because of difficulties in deliveries. Roads may be difficult to travel for delivery vehicles, and rivers may be frozen limiting barge traffic. In addition, suppliers may be hard pressed to keep up with demand when the entire region has been hit by a prolonged sequence of winter storms. Consideration of supply and demand uncertainty issues when determining the safety stock will be critical to a successful inventory management strategy.

Also, the issue of perishability or shrinkage has been identified in the academic literature as an important aspect to the inventory decisions. If the quality of the materials deteriorates as it is stored for longer periods, the deterioration costs must be traded-off with keeping large supplies for level-of-service and pricing opportunity reasons. Although the project did not investigate this issue specifically, consideration of perishability may be important when deciding on end-of-season stocking strategies.

Finally, the management of inventories requires attention specific to each storage location, as well as coordination with an overall region and/or statewide plan. Planning, coordination and setting of guidelines must consider the whole collection of storage locations. Responding to individual storms and replenishing stocks of materials requires decision making at a particular storage location. For an overall inventory management strategy to be most effective, coordination of information and decisions across multiple storage locations is necessary. The following section on supply chain management will address issues that become relevant in this multiple-storage location environment.

## 2.2. Supply Chain Management Literature

A second area of interest is in supply chain management. There has been intense interest in the area of supply chain management over the last 10-15 years. While inventory control is concerned with the day to day details of the ordering and usage operations, supply chain planning considers the longer term contract and coordination issues. With the advent of suppliers and manufacturers that are tightly linked by electronic networks, there have been large improvements in supply chain planning in recent years.

In recent years, the relationship between buyers and suppliers has received considerable attention, due to the globalization of markets, corporate restructuring, and increased focus on costs, quality flexibility, technology, and an expanded role for procurement. Previously, purchasing was considered as a clerical function, where the relationship between buyers and suppliers were adversarial, but now many organizations have employed a more collaborative approach to procurement planning (McHugh et al., 2003).

Typically, industry based supply chain networks include suppliers, manufacturers, distributors and customers [Nahmias, 2001]. Industry based software suites in supply chain management focus in two main areas: planning and execution. "Supply chain execution" is essentially the detailed inventory control (triggering of orders, etc.) described in the previous section. Some of the issues that complicate the inventory control problem (uncertainty in supply availability, price, delivery lead time, etc.) can be mitigated with careful supply chain planning and coordination. Manufacturers now rely on complex supply chain planning and execution software suites to manage contract, ordering and distribution functions more efficiently. There should be opportunities to use the best aspects of these systems to more efficiently manage winter maintenance materials. This includes the development of contract terms with suppliers that mitigate the most costly and disruptive aspects of supply and re-supply of materials. It also includes possible storage and distribution strategies that lower the overall cost and risk, while maintaining high levels of service. Finally, it may require the "visibility" of current stock levels to centralized inventory planners that must place orders and re-distribute stocks.

Concepts such as vendor managed inventories have been very successful in the distribution of consumer goods (for example, see http://www.vendormanagedinventory.com). In these systems, suppliers are responsible for maintaining stock levels at distribution and retail locations. In very well coordinated supply chains in the retail and manufacturing industries, electronic links allow suppliers to directly view the state of inventories and take action on re-ordering. Over time, these levels of coordination can lead to strong partnerships that lead to increasing benefits, decreasing shortages as well as a decrease in inventory levels. With direct supplier involvement in managing inventories, the supplier is more focused than ever in providing great service. Direct visibility of stock levels by the supplier can also help to identify priorities (replenishing for stock or a shortage?). Together these initiatives can help reduce supply lead times, decrease supply uncertainties and otherwise mitigate the factors that require holding large safety stocks. According to [Schwarz, 2004], the sharing of information alone can account for a large fraction of the supply chain improvements seen in recent years.

Another theme in the supply chain literature is the use of transshipments between storage locations, rather than orders from the supplier, to bring inventory levels up to target amounts [Rudi, et.al, 2001]. Depending on transportation costs, transshipment may be an attractive alternative to re-stocking materials, particularly late in a winter season. For example, one storage location may have had a lower usage rate than some nearby locations. In that case, moving stock between the locations, or planning to use the well-stocked location during a storm, may be the most cost effective way to fulfill the demand for materials.

In the automotive industry, Honda and Toyota have built great supplier relationship following six distinct steps (Liker et al., 2000): First, they understand how their suppliers work. Second, they turn supplier rivalry into opportunity. Third, they supervise their vendors. Fourth, they develop their supplier's technical capabilities. Fifth, they share information intensively but selectively. And sixth, they conduct joint improvement activities. Toyota and Honda have succeeded not because they use one or two of these elements but because they use all six elements. The supplier partnering hierarchy is described below:

- **Conduct joint improvements activities**
    - Exchange best practices with suppliers.
    - Initiate continuous improvements (*Kaizen*) in projects at supplier's facilities.
    - Set up supplier study groups.
- **Share information intensively but selectively**
    - Set specific times, places, and agendas for meetings.
    - Use rigid formats for sharing information.
    - Insist on accurate data collection.
    - Share information in a structured fashion.
- **Develop suppliers technical capabilities**
    - Build suppliers problem-solving skills.
    - Develop a common lexicon.
    - Hone core supplier's innovation capabilities.
- **Supervise your suppliers**
    - Send monthly report cards to core suppliers.
    - Provide immediate feedback.
    - Get senior managers involving in solving problems.
- **Turn supplier rivalry into opportunity**

    - Source each component from two or three vendors.
    - Create compatible production philosophies and systems.
    - Set up joint ventures with existing suppliers to transfer knowledge and maintain control.
- **Understand how suppliers work**
    - Learn about suppliers businesses.
    - Go see how suppliers are working.
    - Respect supplier's capabilities.
    - Commit to co-prosperity.

Unlike most other companies Toyota and Honda take trouble to learn all they can about their suppliers. They believe that they can create the foundation of partnership only if they know as much as they can about their suppliers as they know about themselves (Cusumano et al., 1999). Neither Toyota nor Honda depends on a single supplier for everything. Both of them develop two or three suppliers for every component or raw material they buy (Pilkington et al., 1999). They may not want ten different sources, as is often the case in some US companies (Liker et al., 2004), but they encourage competition between vendors right from the product development stage.

In contrast, the salt ordering situation for ODOT differs from the automotive setting because of an important structural difference: The ODOT contracting process solicits and establishes a contract for each county each year that results in a single supplier for each county. The level of inventories kept at the county is thus critical since a secondary source of supply may be difficult or impossible to obtain if the counties contracted supplier is not able to deliver reliably. This single source model also emphasizes the need for a collaborative relationship between ODOT and the suppliers to make continual improvements in trust, communication, technical capabilities, supplier supervision and cooperation.

## 2.3. Winter Maintenance Industry

Industry groups such as the Salt Institute (www.saltinstitute.org) are a significant source of background information. There is a detailed science to the materials used and their mode of application in order to ensure that roads are clear [TAC Report, 2003]. This includes pre-treatment of roads prior to a storm, as well as treatment after a snowfall. This project's effort's did not explore these issues in particular, although knowledge of issues related to application of the materials has been useful. For example, the extent to which materials are used for pre-treatment will impact the types of storage used.

Salt is typically used at the county garages to create brine solution that is used for pre-treatment. The amount of time in storage and the type of storage can have a large impact on how easily the materials can be spread. For example, salt that has been exposed to the weather and saturated with water can be much more difficult to spread and must be spread at a higher rate to ensure coverage when it is wet. [Hampshire, 1999] Also, salt stockpiles can be depleted by exposure to rain.

There has been a significant amount of work in the last 10 years on the topic of the location of materials and the specific routes used for its distribution. This is an important topic, because effective location and distribution are major drivers of cost and effectiveness of winter storm operations. Because it is outside the scope of the current project, these issues have not be addressed in detail in this project. There may be opportunities to extend the efforts of the current project to the location and distribution problems. In light of rising fuel costs, this is a potentially an important method of controlling costs.

# 3. Development of the (*R*, *S*)-inventory guideline

The methodology for developing the (*R*, *S*)-inventory guideline for each Ohio county is summarized in this chapter. The first two sections describe the guideline and its development. This includes development of the (*R*, *S*)-inventory guideline, and the (*R*, *S*)-inventory guideline weather severity index application. These sections provide the theoretical underpinning of the guideline development methodology. Section 1.4 provides the practical expression of this theory as a set of implementable guidelines for each county. The third section reviews supply chain management and gives insight into why an effective inventory guideline is an important component of supply chain management especially as it applies to bulk commodities.

## 3.1. Overview of the Guideline Structure

The (*Q*, *r*) inventory model. as described in Hopp and Spearman (2000) determines the amount of stock to carry and how much to order at one time in a continuous review setting. It is designed for situations with random demand, delivery lead-times and fixed ordering costs. The cost formulation in the (*Q*, *r*) model is then minimized to determine the order quantity (*Q*) and the optimal reorder point (*r*). A simplified result presented here is based on the assumption of normally distributed lead-time demand. The reorder quantity is found by solving the equation,

$$Q^* = \sqrt{\frac{2AD}{h}}\ .$$

Where *A* = the purchase order cost of a replenishment (in \$), *D* = demand rate (in units per year), and h = holding cost (in \$/unit/year). The quantity to order when the inventory falls to or below the reorder point is given by this equation. The reorder point is then calculated by solving the equation, $r^* = \Theta + \mathrm{Z}\sigma$. Where $\Theta$ is the expected demand during the replenishment lead time and $\sigma$ equals the standard deviation of demand during the replenishment lead time. The $\mathrm{Z}$ is then calculated by using an equation based on stockout costs or backorder costs. The stockout cost version is found by solving the equation,

$$\Phi(\mathrm{Z}) = \frac{KD}{KD + hQ}$$

($\Phi(\,)$ is the standard normal CDF) where $K$ is the cost per stockout (in \$), *D* is the yearly demand, and *h* is the annual unit holding cost (in \$ per unit per year). The backorder version is utilized by substituting the backorder cost ($b$) in for $KD$ and holding cost ($h$) for $hQ$.

Whereas the ($Q$ ,$r$)-inventory guideline is applied in a continuous review setting, the ($s$, $S$) guideline, is used for a periodic review situation. In the ($s$, $S$) guideline as described by Parlar et. al. (1995), $s$ is the reorder point. Each period the inventory level is checked and if the inventory level is above $s$ then we do not order. If the inventory level ( $x$ ) is below $s$ then we order up to a level of $S$. The amount to be ordered is dictated by whether the inventory level is $x \leq s$. If this statement is true then the order quantity in a ($s$, $S$)-inventory guideline would be $S$ - $x$. When there is a lead-time for deliveries, pipeline inventories must be added to on-hand inventories in these decisions.

An ($R$, $S$)-inventory guideline is a combination of the ($Q$ ,$r$) and ($s$, $S$) inventory models. The ($R$, $S$)-model was investigated in a paper by Roelants and Muyldermans (2002) for management of salt inventories. It utilizes the continuous review reorder point and the target or order up to level of the periodic review system. The purpose of the model is to determine when to order and how much material should be ordered. This is different than the ($Q$ ,$r$) model which allows orders to be placed at any time, but always orders the same amount. The periodic review ($s$, $S$) inventory guideline places orders at pre-determined times, with varying order amounts. In a ($R$, $S$)-inventory guideline a reorder point ( $R$ ) is established and also a stock/target level ( $S$ ) are found to determine the goals of the model. To protect from shortages during the lead times a safety stock ( $ss$ ) is also included in the reorder point ( $R$ ).

## 3.2. The ($R$, $S$)-inventory guideline weather severity index application

In a paper by Roelants and Muyldermans (2002), an ($R$, $S$)-inventory guideline was investigated to determine when and how much salt to order during the winter months to match inventories closer to actual demand of salt. The actual demand of the salt occurs during the winter months when inclement weather results in road crews treating roads to make them safe for travel. When the salt inventory reaches or falls below the reorder point ( $R$ ) an order is placed, which when delivered brings the inventory level back to its target level ( $S$ ). These parameters ( $R$ ) and ( $S$ ) should vary during the winter period and are established using the idea of a predefined service level. The service level refers to the fraction of demands that can be met without a shortage. The service level suggested by Roelants and Muyldermans (2002) is set to a very high 99.8%. This reflects the very high social and economic impacts in a region if roads cannot be treated and snow and ice is not cleared. The service level is thus set very high to make stockouts very rare. In the paper the guideline is developed by utilizing two techniques. One is a multi-linear regression, where past weather variables are matched up with past salt usage for corresponding days to develop a model. The second makes use of the statistics of historical salt usage data for the region and computes the ($R$, $S$) parameters directly from these values. These ($R$, $S$)-inventory guideline models contrast with the typical practice of stocking the salt domes to capacity during the summer months and only reduce inventories sometimes towards the end of the winter season. Inventories left over at the end of the winter season are held and maintained until the following winter. This incurs costs and ties up capital. For example costs are incurred to prevent the deterioration of salt.

For the multi-linear regression model, winter weather types are classified in the Roelants paper from A to G and days during each month for each weather type were counted. The letter A signifies the lightest winter weather event, while G is the most severe. A regression model was developed with the salt usage as the dependent variable and the weather event data as the independent variables. Using the statistics of the model output the (*R*, *S*)-inventory guideline parameters are calculated.

The reorder point is calculated using this equation (1).

$$R = ss + \mu_{LT} \tag{1}$$

The mean demand during the lead time ( $\mu_{LT}$ ) is the mean of the predictions.

The safety stock ( $ss$ ) is computed from the standard deviation of the predicted demand during the lead time ( $\sigma_{LT}$ ). The $\sigma_{LT}$ is then multiplied by the safety factor $k$ . For a Normal model of the variation in demand the value of *k* is 2.88, based on a 99.8% service level.

$$ss = k\sigma_{LT} \tag{2}$$

$$S = R + E\left[\text{weekly demand}\right] \tag{3}$$

This approach for setting the target level assumes that orders are placed approximately once per week on average. This approach allows the target stock level to be based on average weekly usage, rather than requiring an estimate of ordering and holding costs, as in the EOQ-type models. Because these cost parameters are difficult to estimate, this is a preferred method of implementing the ordering guidelines in practice.

In this project the $\mu_{LT}$ and $\sigma_{LT}$ values were computed separately for each month of the winter season. For example, there is a different $\mu_{LT}$ and $\sigma_{LT}$ for each of November, December, January, February, and March. Because of this, each month has a different R and S value. A more detailed model could be developed that has R and S values that change weekly, for example.

Instead of using a multi-linear regression with weather variables the Roelants paper also suggests a second method utilizes historical salt usage directly to estimate values for the parameters $\mu_{LT}$ and $\sigma_{LT}$ for each month. The (R ,S)-guideline values are calculated based on the same procedure based on equations (1) – (3). The findings of the Roelants and Muyldermans paper is that the first model using multi-linear regression with weather events is more accurate than using historical data, but requires more data and time. The second model using the historical data is less accurate, but is easier to use and requires less data. Overall the second method tends to result in guidelines that wait a small amount of time longer to reorder.

In an effort to determine relationships between winter activities and different weather conditions, Indiana developed a weather severity index to estimate total costs per mile. The paper written by McCullouch, Belter, Konieczny, and McClellan (2004) reviews many other weather severity indices developed by Wisconsin DOT, Washington State DOT, Hulme, and Strategic Highway Research Program Index (SHRP). It also develops a weather severity index for Indiana for the purpose of calculating costs per lane mile during winter weather activities. These other indices found no significant correlation between costs per mile and Indiana's weather factors. They also concluded that some of the weather factors that they thought important were missing. Similar to the methods used by Roelants and Muyldermans, the Indiana Weather Severity Index was developed using multi-linear regression. The lane mile costs were the dependent variable and weather variables were independent variables in the regression. The paper by McCullouch et. al. (2004) introduces the weather variables and where these weather factors can be found. They found that the most influential weather factors were the number of days of frost, freezing rain, drifting of snow, and snow events. After performing the regression with these four factors they began to add other factors such as average temperature, storm duration, and snow depth. The result was that as more weather factors were added to the regression, the closer the predictions got to the actual costs per lane mile. It was also found that due to different climatic zones of Indiana that one regression model for the entire state was not appropriate. The state was thus broken up into four regions and data for the major city in each of the zones was used in the regression model.

## 3.3. Supply chain management as used in bulk commodities

In Lambert and Cooper (2000) supply chain management is defined as the integration of business processes from suppliers that add value through the end user. In Bowersox et al. (2002) supply chain management consists of firms collaborating to improve efficiency, which requires managing processes across the different functional areas of a company and linking them with outside partners and customers. To better understand the supply chain management definition, Handfield and Nichols (1999) defined what a supply chain is and what it encompasses. Their definition is that a supply chain includes all activities associated with the flow and transformation of goods from raw materials to the end user, as well as all the associated information flows between partners. Integrating all of these activities to improve relationships throughout the supply chain to achieve competitive advantages is supply chain management. This should not be confused with logistics which is defined by Lambert and Cooper (2000), "…as that part of the supply chain that plans, implements, and controls the efficient, effective flow and storage of goods, services, and related information from point-of-origin to point-of-consumption in order to meet customers' requirements". This definition of Logistics was presented to the Council of Logistics Management in 1998 and was a revision of the 1986 definition. Within a corporation the supply chain includes purchasing, marketing and sales, finance, research and development, production, and logistics. Outside the firm the supply chain includes suppliers, customers, and end consumers. The integrating and managing of all these business processes is supply chain management.

The supply chain corresponding to suppliers and consumers of salt is similar to that of the supply chain of a major propane gas distributor in Illinois presented in Chiang and Russell (2003). The propane gas supply chain in this case is a four-level system where propane producers supply regional supply terminals. These propane supply terminals are supplied by way of rail, pipeline, or truck. Distributor-owned storage plants are then responsible for the purchase and transportation of the propane to their own storage plants. These storage plants then supply the retail customers. In some cases the distributor has a supply contract with a particular supplier terminal. Because propane gas is a major heating source for many homes, the propane supply chain sees a spike in demand during the cold winter months in the region. The purpose of the paper is to select supply terminals for distributors for efficient and effective supply of propane inventories. The selection should be based on minimizing distance to help ensure uninterrupted supply and also for minimizing distribution costs. The price of propane gas is similar to that of gasoline and thus profits are related to the purchase price and the travel expenses related to moving the propane gas from the supply terminal to the distributor locations.

The supply chain of salt is very similar in that suppliers must position their stockpiles within close proximity of county garages to cut costs and attain a high service level during the peak demand months. Because salt is used during the winter time there is the similar peak in demand during the winter months like propane. In the propane gas example the propane supply chain had a four level system that is very similar to the road salt supply chain. Unlike propane, salt is mined and then distributed, with minimal processing required. Mining corresponds to the beginning of the supply chain. The salt taken from the mine is then deposited at a vendor stockpile, which is very similar to the regional supply terminal for the propane example. The salt is then transferred from the vendor stockpile locations to stockpiles in the state of Ohio by way of rail or barge. These Ohio stockpiles are owned by the salt companies and are like the distributor-owned propane storage plants. From the stockpile the salt is moved by over-the-road trucks to county garages owned by the state of Ohio. The county garages are the customer for the salt company just like the retail customers in the propane example.

Unlike the propane example the state of Ohio sets up annual supply contracts between the vendors and each county. The contracts are bid each year and salt vendors are awarded individual county contracts that specify a price per ton of salt. For a vendor to win a contract they are required to locate stockpiles in Ohio. To quote the lowest prices and establish a very high service level the vendors must choose effective locations for the Ohio stockpiles. The price per ton paid by the state includes transportation to the garages, so the smaller the distance the lower the price of salt and also the higher the service level. Although the supply chain described in Chiang and Russell (2003) is similar in structure in the ways described above, the paper does not focus on the inventory stocking decisions. It does focus on the stockpile location problem, which was outside the scope of this project.

The article by Kaplan (2002) is more instructive in its discussion of coal supplies in the power generation industry. Kaplan indicates how the average utility stockpile of coal in the U.S. has decreased in terms of number of number of days of supply from the 1950's through 2000. The number of days of supply for coal kept in inventory in the electric power generation industry has decreased from around 100 days of supply in 1950 to about 35 days in 2000. As described in the earlier sections on supplier relations industry, decreasing inventory levels in many industries represent a closer cooperation, lower levels of uncertainty and a growing sense of integration between suppliers and producers. The article by Kaplan uses a Monte Carlo simulation technique similar to that employed by this project to investigate the effect of coal supply disruptions on the continued operation of a hypothetical 500 MW generating station. With a very simple model they investigate the cost of unlikely supply disruptions, in terms of using alternate energy supplies. The article is instructive because it emphasizes the need to consider the impact of unlikely events, both in terms of the effect on operations, as well as the cost to maintain service during a supply disruption.

One of the insights from the review of supply chain management, logistics, and bulk commodities such as propane is the importance of the effective flow of information between partners in a supply chain. Information such as locations of customers and suppliers is important in the determination of service level and the need to efficiently place suppliers close to the end user to effectively fill orders. To effectively fill orders suppliers must receive orders from their customers in a timely and effective way so as to minimize disruption due to shortage in the supply chain. An ineffective inventory guideline that creates orders in an arbitrary way can cause disruptions in the supply chain.

The following chapters detail the models and results used to develop inventory guidelines for each county in Ohio, with an integration of the philosophical and technical approaches we found while investigating the related literature.

# 4. The Weather Regression Model

In this chapter we take the findings from McCullouch et al. (2004) and use them to help determine which weather variables are significant in the development of weather regression models for the regions of Ohio. The McCullouch et al. (2004) paper is helpful through its procedure and insight into the development of a weather index for Indiana by selecting the most important weather variables relevant to the usage of salt. Throughout this section the variables for each city/county are determined by comparing the accuracy of the regression models that include different combinations of weather variables. The results are a weather regression model that supports predicted salt usage for the major Ohio counties based on the observed weather. These are used in Chapter 5 to calculate the (*R*, *S*)-inventory guideline parameters.

## 4.1. Defining the significant weather variables

Taking the information from the two models investigated by Roelants and Muyldermans (2002) and McCullouch et al. (2004) a weather regression model for each of the Counties of Ohio was developed. To make the process simpler a spreadsheet in Excel was developed that would collect weather variables imported from weather files from the National Climatic Data Center (NCDC) and the National Oceanic and Atmospheric Administration (NOAA) web sites. Figure 4.1 is an example of the data files that are available on the NOAA web site. Figure 4.1 shows the variety of data available for each major city in Ohio in a specific month of a year.

# DECEMBER 2003
# LOCAL CLIMATOLOGICAL DATA
NOAA, National Climatic Data Center

# AKRON, OH
AKRON-CANTON REGIONAL ARPT (CAK)

Lat: 40° 55' N Long: 81° 26' W Elev (Ground): 1238 Feet

Time Zone: EASTERN WBAN: 14895 ISSN #:0198-3881

| DATE | TEMPERATURE °F MAXIMUM | MINIMUM | AVERAGE | DEP FROM NORMAL | AVERAGE DEW PT | AVERAGE WET BULB | DEG DAYS BASE 65° HEATING | COOLING | WEATHER | SNOW/ICE ON GND (IN) 0700 LST DEPTH | 1800 LST WATER EQUIV | PRECIPITATION (INCHES) 2400 LST SNOW-FALL | 2400 LST WATER EQUIV | PRESSURE (INCHES OF HG) AVERAGE STATION | AVERAGE SEA LEVEL | WIND RESULTANT SPEED | RES DIR | AVERAGE SPEED | MAXIMUM 5-SEC SPEED | DIR | MAXIMUM 2-MIN SPEED | DIR | DATE |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15 | 16 | 17 | 18 | 19 | 20 | 21 | 22 | 23 | 24 |
| 01 | 46 | 32 | 39 | 4 | 24 | 32 | 26 | 0 | | 0 | | 0.0 | 0.00 | 28.78 | 30.12 | 17.4 | 28 | 18.0 | 39* | 30 | 31* | 30 | 01 |
| 02 | 34 | 23 | 29 | -6 | 15 | 24 | 36 | 0 | SN | 0 | | T | T | 29.06 | 30.41 | 9.3 | 30 | 9.7 | 28 | 29 | 22 | 30 | 02 |
| 03 | 33 | 24 | 29 | -6 | 19 | 25 | 36 | 0 | | 0 | | 0.0 | 0.00 | 29.15 | 30.51 | 2.5 | 11 | 4.0 | 12 | 08 | 10 | 09 | 03 |
| 04 | 40 | 25 | 33 | -1 | 19 | 28 | 32 | 0 | | 0 | | 0.0 | 0.00 | 28.92 | 30.28 | 9.1 | 08 | 9.5 | 16 | 09 | 14 | 09 | 04 |
| 05 | 34 | 31 | 33 | -1 | 31 | 33 | 32 | 0 | RA SN FG+ FZFG BR | 7 | 0.3 | 6.5 | 0.65 | 28.65 | 30.00 | 11.4 | 07 | 14.1 | 25 | 06 | 21 | 05 | 05 |
| 06 | 33 | 27 | 30 | -4 | 27 | 29 | 35 | 0 | SN BR | 7 | 0.9 | 0.3 | 0.03 | 28.79 | 30.15 | 7.5 | 33 | 9.1 | 23 | 31 | 18 | 31 | 06 |
| 07 | 29 | 16 | 23 | -10 | 20 | 23 | 42 | 0 | SN BR | 5 | 0.8 | T | T | 28.83 | 30.19 | 5.8 | 29 | 6.2 | 18 | 30 | 15 | 30 | 07 |
| 08 | 33 | 16 | 25 | -8 | 22 | 25 | 40 | 0 | | 4 | 0.9 | 0.0 | 0.00 | 28.79 | 30.16 | 5.6 | 15 | 5.9 | 14 | 13 | 12 | 13 | 08 |
| 09 | 40 | 31 | 36 | 3 | 34 | 35 | 29 | 0 | RA DZ BR | 4 | 0.8 | 0.0 | 0.02 | 28.70 | 30.05 | 7.3 | 14 | 7.6 | 14 | 15 | 13 | 15 | 09 |
| 10 | 44 | 40 | 42 | 10 | 40 | 42 | 23 | 0 | RA BR | T | | 0.0 | 0.27 | 28.33 | 29.65 | 10.6 | 13 | 11.1 | 24 | 12 | 18 | 13 | 10 |
| 11 | 45 | 27 | 36 | 4 | 30 | 33 | 29 | 0 | RA SN BR | 0 | | T | 0.03 | 28.43 | 29.76 | 14.9 | 28 | 15.7 | 35 | 30 | 28 | 29 | 11 |
| 12 | 27 | 19 | 23 | -9 | 16 | 22 | 42 | 0 | SN | 0 | | T | T | 28.85 | 30.22 | 11.1 | 28 | 11.3 | 25 | 28 | 21 | 28 | 12 |
| 13 | 27 | 14* | 21 | -11 | 16 | 21 | 44 | 0 | SN | T | | T | T | 28.99 | 30.36 | 4.6 | 08 | 7.4 | 18 | 10 | 15 | 10 | 13 |
| 14 | 33 | 25 | 29 | -2 | 28 | 28 | 36 | 0 | SN BR | 3 | 0.4 | 3.7 | 0.25 | 28.57 | 29.92 | 2.6 | 11 | 8.5 | 18 | 30 | 15 | 28 | 14 |
| 15 | 29 | 25 | 27 | -4 | 26 | 27 | 38 | 0 | SN BR | 4 | 0.3 | T | T | 28.71 | 30.07 | 7.1 | 22 | 11.5 | 24 | 16 | 20 | 28 | 15 |
| 16 | 46 | 26 | 36 | 5 | 32 | 35 | 29 | 0 | RA BR | 3 | | 0.0 | 0.14 | 28.53 | 29.87 | 11.2 | 19 | 13.9 | 28 | 28 | 23 | 28 | 16 |
| 17 | 34 | 24 | 29 | -1 | 23 | 26 | 36 | 0 | SN BR | T | | 1.3 | 0.06 | 28.46 | 29.80 | 15.5 | 26 | 15.7 | 26 | 26 | 22 | 26 | 17 |
| 18 | 28 | 23 | 26 | -4 | 20 | 24 | 39 | 0 | SN BR | 3 | | 0.7 | 0.03 | 28.44 | 29.79 | 9.8 | 26 | 10.1 | 26 | 26 | 22 | 26 | 18 |
| 19 | 27 | 25 | 26 | -4 | 24 | 25 | 39 | 0 | SN BR HZ | 1 | | 1.8 | 0.11 | 28.49 | 29.84 | 8.1 | 26 | 8.3 | 17 | 27 | 15 | 27 | 19 |
| 20 | 26 | 15 | 21* | -8 | 17 | 21 | 44 | 0 | SN BR | 3 | 1.6 | 0.5 | 0.04 | 28.78 | 30.15 | 9.2 | 28 | 10.3 | 22 | 30 | 18 | 29 | 20 |
| 21 | 38 | 19 | 29 | 0 | 18 | 25 | 36 | 0 | | 1 | | 0.0 | 0.00 | 28.81 | 30.17 | 15.4 | 21 | 15.5 | 28 | 21 | 23 | 21 | 21 |
| 22 | 43 | 33 | 38 | 9 | 30 | 35 | 27 | 0 | RA BR | T | | 0.0 | 0.04 | 28.69 | 30.03 | 11.7 | 21 | 11.8 | 22 | 22 | 18 | 21 | 22 |
| 23 | 48 | 32 | 40 | 11 | 41 | 42 | 25 | 0 | RA SN BR | 0 | | 0.4 | 0.52 | 28.48 | 29.80 | 12.5 | 20 | 14.4 | 30 | 19 | 23 | 19 | 23 |
| 24 | 33 | 28 | 31 | 3 | 29 | 31 | 34 | 0 | SN BR | 1 | | 1.4 | 0.14 | 28.54 | 29.88 | 8.3 | 26 | 8.8 | 20 | 29 | 15 | 28 | 24 |
| 25 | 28 | 24 | 26 | -2 | 21 | 24 | 39 | 0 | SN FZFG BR | 1 | | 2.1 | 0.12 | 28.70 | 30.06 | 12.4 | 25 | 12.8 | 26 | 27 | 22 | 23 | 25 |
| 26 | 33 | 25 | 29 | 1 | 23 | 26 | 36 | 0 | SN BR | 3 | 0.2 | T | T | 28.95 | 30.33 | 8.7 | 28 | 9.1 | 17 | 30 | 15 | 29 | 26 |
| 27 | 41 | 20 | 31 | 3 | 22 | 27 | 34 | 0 | BR HZ | 1 | | 0.0 | 0.00 | 28.99 | 30.37 | 3.0 | 18 | 4.7 | 13 | 13 | 10 | 13 | 27 |
| 28 | 53 | 29 | 41 | 14 | 24 | 34 | 24 | 0 | | T | | 0.0 | 0.00 | 28.83 | 30.18 | 8.3 | 17 | 9.1 | 20 | 19 | 17 | 19 | 28 |
| 29 | 53* | 36 | 45* | 18 | 33 | 41 | 20 | 0 | RA | 0 | | 0.0 | 0.09 | 28.60 | 29.93 | 10.5 | 19 | 10.8 | 22 | 18 | 18 | 18 | 29 |
| 30 | 46 | 25 | 36 | 9 | 27 | 30 | 29 | 0 | RA SN BR | T | | T | 0.37 | 28.75 | 30.10 | 12.3 | 26 | 13.1 | 38 | 31 | 30 | 31 | 30 |
| 31 | 46 | 26 | 36 | 9 | 27 | 33 | 29 | 0 | | 0 | | 0.0 | 0.00 | 28.87 | 30.23 | 11.5 | 22 | 12.7 | 32 | 24 | 28 | 22 | 31 |
| | 37.0 | 25.3 | 31.2 | | 25.1 | 29.3 | 33.5 | 0.0 | < MONTHLY AVERAGES TOTALS-> | | | 18.6 | 2.91 | 28.73 | 30.08 | 5.0 | 24 | 10.7 | <-MONTHLY AVERAGES | | | | |
| | -.7 | 1.7 | 0.5 | | <---------------DEPARTURE FROM NORMAL---------------> | | | | | | | | -.07 | SUNSHINE, CLOUD, & VISIBILITY TABLES ON PAGE 3 | | | | | | | | | |

## DEGREE DAYS

| | MONTHLY TOTAL | MONTHLY DEPARTURE | SEASON TO DATE TOTAL | SEASON TO DATE DEPARTURE |
|---|---|---|---|---|
| HEATING: | 1040 | -7 | 2219 | -96 |
| COOLING: | 0 | 0 | 552 | -126 |

GREATEST 24-HR PRECIPITATION: 0.66 DATE: 05-06
GREATEST 24-HR SNOWFALL: 6.5 DATE: 05
GREATEST SNOW DEPTH: 7 DATE: 06+

| | SEA LEVEL PRESSURE | DATE | TIME |
|---|---|---|---|
| MAXIMUM : | 30.60 | 03 | 0951 |
| MINIMUM : | 29.46 | 10 | 2251 |

NUMBER OF DAYS WITH →

| | | | | | |
|---|---|---|---|---|---|
| MAXIMUM TEMP ≥ 90: | 0 | MINIMUM TEMP ≤ 32: | 28 | PRECIPITATION ≥ 0.01 INCH: | 17 |
| MAXIMUM TEMP ≤ 32: | 10 | MINIMUM TEMP ≤ 0: | 0 | PRECIPITATION ≥ 0.10 INCH: | 9 |
| THUNDERSTORMS: | 0 | HEAVY FOG: | 1 | SNOWFALL ≥ 1.0 INCH: | 6 |

DECEMBER 2003
AKRON, OH

**Figure 4.1 - NOAA monthly weather data**

The spreadsheet was developed so that the weather variables being considered could be altered by making small changes in the spreadsheet parameters. This allows a variety of different weather variables to be considered, a feature used in developing the most accurate weather regression model. The weather variables were accumulated by week. These weeks were then accumulated into their corresponding calendar month. All the months were then accumulated for the range of years over which the study is being conducted. These weekly weather variables were matched up with the corresponding weekly salt usage (by county) from the ODOT databases. Spreadsheet files that accomplish this matching automatically were developed. A linear regression modeling salt usage as a function of weather variables was then fit to the data for each month, using several years of data. These estimates were used to find predicted values of salt usage for each week. After this is done for all of the historical data, the statistics of the predicted usage values are used for the next part of the model which is finding the reorder point, safety stocks, and target stock levels. Figure 4.2 diagrams the process of the formulation of the (*R*, *S*)-inventory guideline.

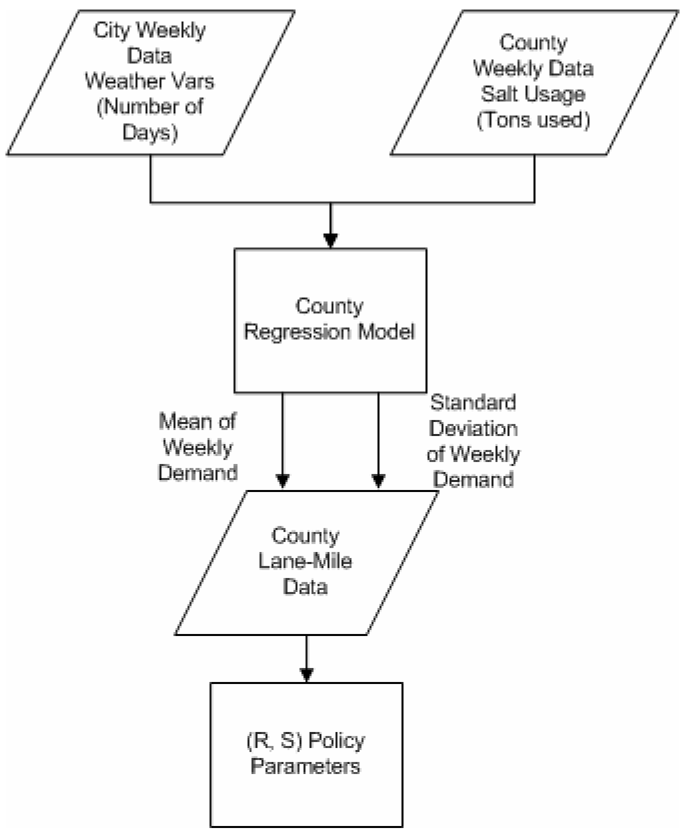



**Figure 4.2 - (*R*, *S*) inventory guideline development process**

Roelants and Muyldermans (2002) found that an (*R*, *S*)- inventory guideline performs better when utilizing the regression output to calculate the mean and variance of usage rather than simply calculating the ($R$, $S$) parameters directly from the historical data. Since the suppliers for Ohio are allowed one week (7 days) in their contracts to make the delivery we consider the lead time as one week. The calculations use weeks as the base time unit instead of months, which differs from Roelants et al. (2002). Each year's data begins on November 4 and ends either March 29$^{th}$ or 30$^{th}$ depending on whether that year is a leap year. This time period constitutes a total of 21 weeks per year for each of the 7 years of data from November 1998 – March 2005. The non-winter months from April – October are not included in the model. For example the first week modeled is from November 4 to November 10. A week is considered to be part of the month in which the week begins. For the model for a county the weather variables are based on the major city in that county and the supporting salt usage data is for the entire county.

The first process in the regression procedure is to determine what variables are most closely related to salt usage. Rather than the weather variables used in Roelants et al., we chose an approach similar to McCullouch et al. in choosing the weather variables. As a start, we considered utilizing the weather variables that were used in developing Indiana's weather severity index in McCullouch et al. (2004).

One very important weather factor identified from the paper is the amount of snow (in.). In the model, this factor is varied by possibly including a variable that represents whether "trace" snowfall is considered as a snow event. From the weather data recorded by NOAA, trace amounts of snow are recorded as .001 (in.). The snowfall amount variable will either include trace amounts of snowfall ( >0 in.) or include only snowfall amounts greater then a trace ( >.001 in.) in total amount of snow fallen. In the same way that snowfall amounts are recorded, the number of days of snowfall in a week are accumulated. Thus there are two options: whether to include a trace snowfall amount as a day of snow or only include measurable snowfall above a trace in the model.

Another weather variable that depends on the treatment of trace amounts of snow is the snow cover or depth on the ground recorded by the weather station at 7 a.m. These variables are easily calculated from the NOAA weather data and can be seen in Figure 4.1 in the representative columns. Two other weather variables considered for the weather regression model are the number of days of freezing rain and blowing snow in the week. These are directly available from the NOAA data. This can be seen in Figure 4.1 in the middle column labeled "weather". This column shows that the freezing rain is signified by "fzr" and blowing snow by "bsn". The final weather variables that were considered for the regression model were minimum, maximum, and average temperatures bounded by a predefined temperature. These variables are optimally bounded by whether they are less than 30 degrees (<30°) or less then 32 degrees (<32°). Table 4.1 lists all the weather variables for the regression model investigated.

**Table 4.1 - Defined weather variables**

| Events | Symbols | Definitions |
|---|---|---|
| Snow | Sn | Amount of Snowfall > 0 in.<br>Amount of Snowfall > 0.001 in. |
| Days of Snow | DSn | Number of days of Snowfall > 0 in.<br>Number of days of Snowfall > 0.001 in. |
| Freezing Rain | FzR | Number of days with Freezing Rain/Freezing Drizzle |
| Blowing Snow | BSn | Number of days with Blowing Snow |
| Snow Cover | SnC | Number of days of ground snow cover > 0 in.<br>Number of days of ground snow cover > .001in. |
| Minimum Temperature | MinT | Number of days with minimum temperature < 30°<br>Number of days with minimum temperature < 32° |
| Maximum Temperature | MaxT | Number of days with maximum temperature < 30°<br>Number of days with maximum temperature < 32° |
| Average Temperature | AveT | Number of days with average temperature < 30°<br>Number of days with average temperature < 32° |

There were two variables in the McCullouch et al. (2004) Indiana weather severity index that are more speculative and were not utilized. The weather variables storm intensity and number of days of frost were not utilized in the model because these are not as clear to define using the NOAA data. As shown in Figure 4.1 there is no column for the length of the storm and there is no clear indication of frost.

## 4.2. Comparisons for finding the combination of weather variables

When choosing the best model, the squared coefficient of determination $R^2$, is used to determine the best combination of weather variables as defined by Montgomery and Runger (2003). To determine which variables are significant a statistical analysis software called JMP 5.1 was used. Within this software there is the ability to simply run the analysis and JMP will pick the most significant variables. This function allows the user to also manually add or remove variables, which is useful in identifying any other important variables that JMP does not find. Upon adding or subtracting the variables the software reports the impacts on $R^2$, $R^2$ adjusted, and also the mean square error. The process for selecting variables consists of adding variables that lower the mean square error, which results in a lower $R^2$ adjusted. According to Montgomery et al. (2003), maximizing the $R^2$ number is not as effective as lowering the mean squared error when it comes to accurate predictions. Comparisons of the different models were made in a systematic exploration of different sets of variables. Each of the comparisons for a month are only used with one set of temperature and snowfall variances. For example the maximum, minimum, and average temperature considered were "less than 30°" or "less than 32°" and all variations of snowfall are varied by "greater than 0 in." or "greater than a trace (.001 inches)".

Each of the regression models was investigated for the 8 major cities and their corresponding counties. This process determined a unique regression model for each of the months of November, December, January, February, and March. The city of Toledo and Lucas County were studied using weather data from the Detroit airport (approximately 50 miles away from the city of Toledo) due to inaccurate weather data from the city of Toledo. Weather data from Detroit was matched with Lucas County salt usage data. The cities and their corresponding counties included in the study were: Akron (Summit County), Cincinnati (Hamilton County), Cleveland (Cuyahoga County), Columbus (Franklin County), Dayton (Montgomery County), Mansfield (Richland County), Toledo (Lucas County), and Youngstown (Mahoning County). Cities in similar weather zones were also analyzed to see if a weather based regression model for salt usage for one city can be utilized for another city. The only areas that were studied to find a common weather regression model were Cleveland, Akron, and Youngstown. These areas are in such close proximity that a common model may be possible.

In the following description, only the results for the city of Cleveland are described in detail to document the development of the regression model. The same methodology was used for the other cities, but only the final results are provided for these other cities. Again the corresponding city weather data was utilized and it is matched with the county's total salt usage. After the development of the models for the 8 major counties, the models for Cuyahoga, Summit, and Mahoning were tested in counties other than the one for which they were originally developed. To do this the models are adjusted by dividing salt usage by the number of lane-miles of road in the county. This mileage information was gathered from the Ohio Department of Transportation web site. This predicted usage per lane-mile was then multiplied by the lane mileage of the new county being studied. This was utilized to test if one weather regression model could be used for more than one county.

The process of determining the most significant weather variables begins after the weather and usage data are collected into the Excel spreadsheet. The most significant weather variables and their parameters were found by using the statistical program JMP. Figure 4.3 shows a graph of points representing observations of salt used and snowfall in inches. A fitted line is superimposed on these points. This figure shows that as the snow increases, the amount of salt used also increases. Another similar graph of points representing the days of snowfall and the corresponding salt usage is shown in Figure 4.4. Days of snowfall (in a week) take discrete values from 0 to 7 days, but usage shows a similar increase as days of snowfall increase. From these two figures we see that a noticeable relationship exists between the weather variables and salt usage. Thus using a linear regression on these variables is appropriate to predict salt usage.

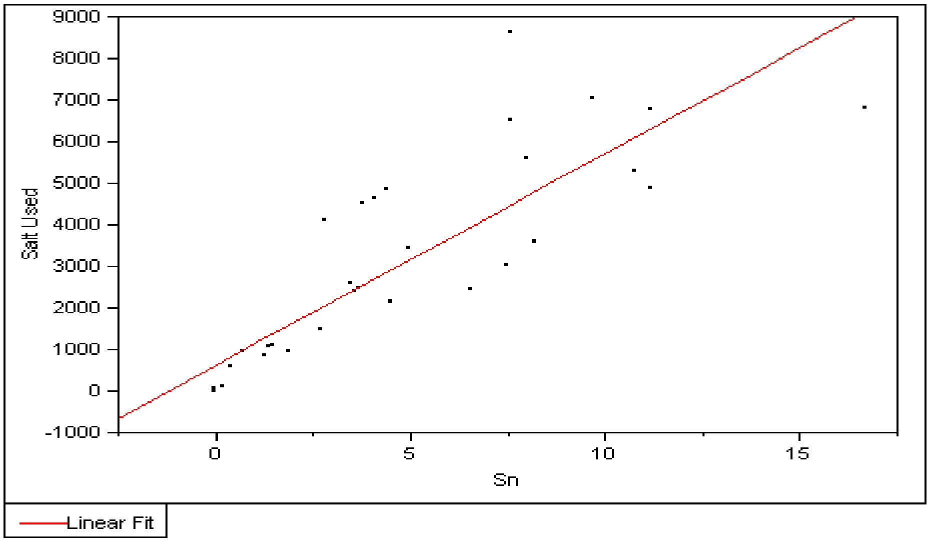



**Figure 4.3 - Salt usage in Cuyahoga vs. snowfall (inches) in January**

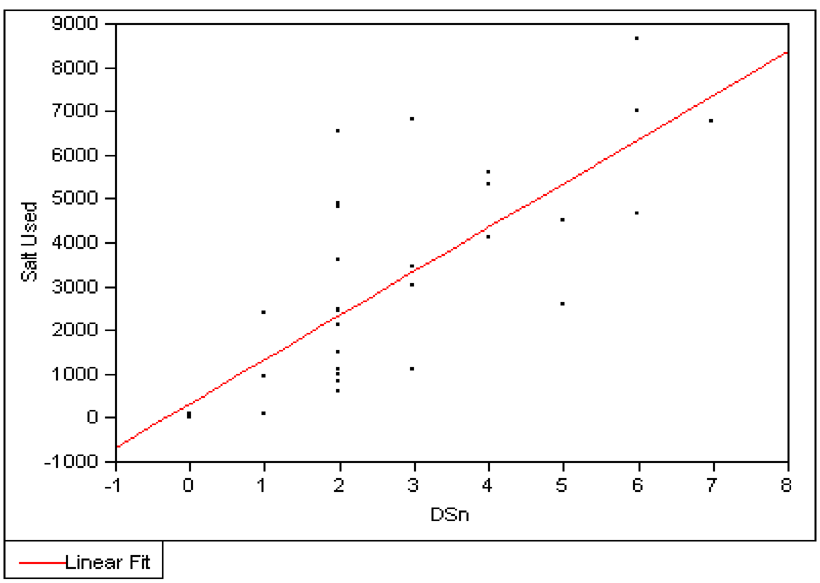



**Figure 4.4 - Salt usage in Cuyahoga vs. number of days of snowfall in January**

## 4.3. Development of Cuyahoga County's weather regression model

For each of the months, the data over the 7 years was run through the JMP statistical program. By utilizing the "stepwise" function in JMP for iteratively fitting a regression model, the significant weather variables and their parameter estimates were found. Each month's significant variables for each combination of snowfall and temperature alternatives were found. These combination of variable alternatives consist of the temperature < 30° F and snowfall > .001 inches, temperature <30° F and snowfall > 0 inches, temperature <32° F and snowfall > 0 inches, and temperature <32° F and snowfall > .001 inches. Overall it was found that for Cuyahoga County the model performs best when the temperature variable used is set to < 30° F and the snowfall variable used is snowfall > .001 inches. The variables under these conditions that are most significant are depicted by an X in the appropriate column of Table 4.2 along with the corresponding $R^2$ number. The table shows that every $R^2$ is above .90 and thus the model provides a very good fit. An $R^2$ of close to 1.0 is considered a near to perfect fit for the model.

**Table 4.2 - Cuyahoga County weather variables provided by JMP**

| Temp. | < 30 | Snowfall | >.001 | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ |
| November | x | x | | | | x | x | x | 0.991 |
| December | x | x | x | | x | | | | 0.921 |
| January | x | | x | | | | | x | 0.951 |
| February | x | x | x | x | | x | | x | 0.937 |
| March | x | x | | x | | | | | 0.920 |

After investigating the variables more closely and examining not only the $R^2$, but also the $R^2$ adjusted and the mean square error (MSE) it was found that changing the variables would lead to an improved model. The only change is in the model for March where instead of using the temperature < 30° F and snowfall > .001 in., the combination of temperature < 32° F and snowfall > .001 in. are used. Under this condition for the month of March the variables being utilized are Sn, DSn, BSn, and AveT. Table 4.3 shows the final variables and the $R^2$ numbers and the mean squared errors for the regression model for Cuyahoga County.

**Table 4.3 - Cuyahoga County weather variables used for the regression model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >.001 | >.001 | | | | <30 | <30 | <30 | 0.991 | 0.989 | 10200 |
| Dec. | >.001 | >.001 | X | | >.001 | | | | 0.921 | 0.911 | 561000 |
| Jan. | >.001 | | X | | | | | <30 | 0.951 | 0.944 | 461000 |
| Feb. | >.001 | >.001 | X | X | | <30 | | <30 | 0.937 | 0.919 | 200000 |
| Mar. | >.001 | >.001 | | X | | | | <32 | 0.927 | 0.914 | 277000 |

The models for Cuyahoga County using the variables as depicted by Table 4.3 are utilized in determining the predicted values of salt usage. These numbers will be used to calculate the (*R*, *S*)-inventory guideline values. A model was constructed for each month and is shown below.

$$\text{Cleveland}_{nov.} = 22.001 + 283.73 * \text{Sn} + 129.63 * \text{DSn} - 997.74 * \text{MaxT} - 50.077 * \text{MinT} + 1255.4 * \text{AveT}$$

$$\text{Cleveland}_{dec.} = -287.88 + 255.94 * \text{Sn} + 357.68 * \text{DSn} + 761.25 * \text{FzR} + 300.87 * \text{SnC}$$

$$\text{Cleveland}_{jan.} = -481.49 + 472.60 * \text{Sn} + 1253.0 * \text{FzR} + 238.55 * \text{AveT}$$

$$\text{Cleveland}_{feb.} = -63.303 + 256.88 * \text{Sn} + 191.81 * \text{DSn} + 355.09 * \text{FzR} + 669.02 * \text{BSn} - 182.39 * \text{MaxT} + 139.69 * \text{AveT}$$

$$\text{Cleveland}_{mar.} = -118.80 + 197.75 * \text{Sn} + 347.23 * \text{DSn} + 559.45 * \text{BSn} - 148.97 * \text{SnC} + 223.73 * \text{AveT}$$

Using the above models the predicted amount of salt used is calculated for each month for each county and is shown in Figures 4.5 – 4.9, along with the actual amount of salt used each month over the 7 year period. Each graph represents the result from a different monthly model, for each of the 5 months. Figure 4.10 then shows the actual vs. predicted from November 1998 – March 2005 excluding the non-winter months of April – October as defined earlier.

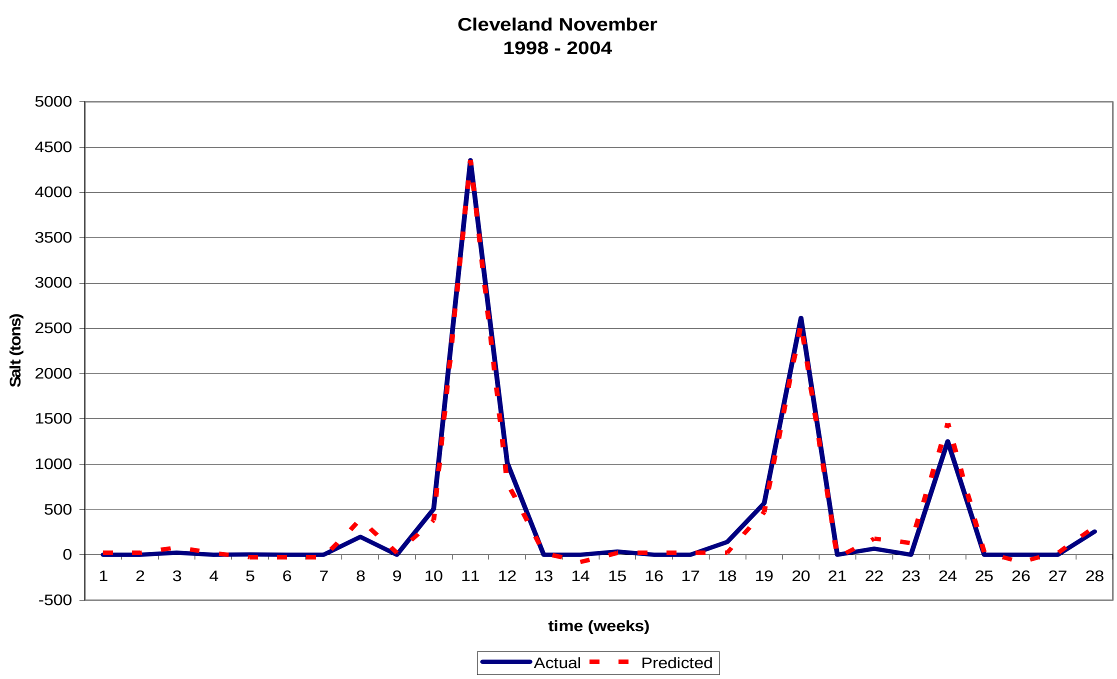



**Figure 4.5 - Cuyahoga November actual and predicted usage**

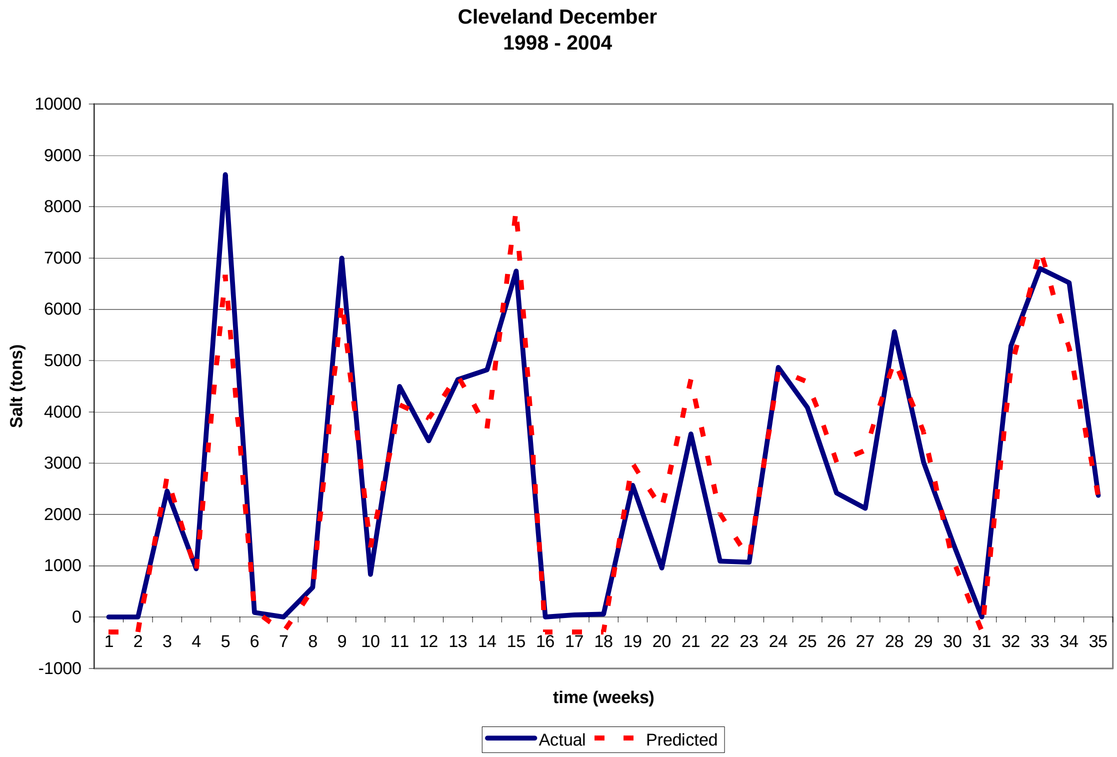



**Figure 4.6 - Cuyahoga December actual and predicted usage**

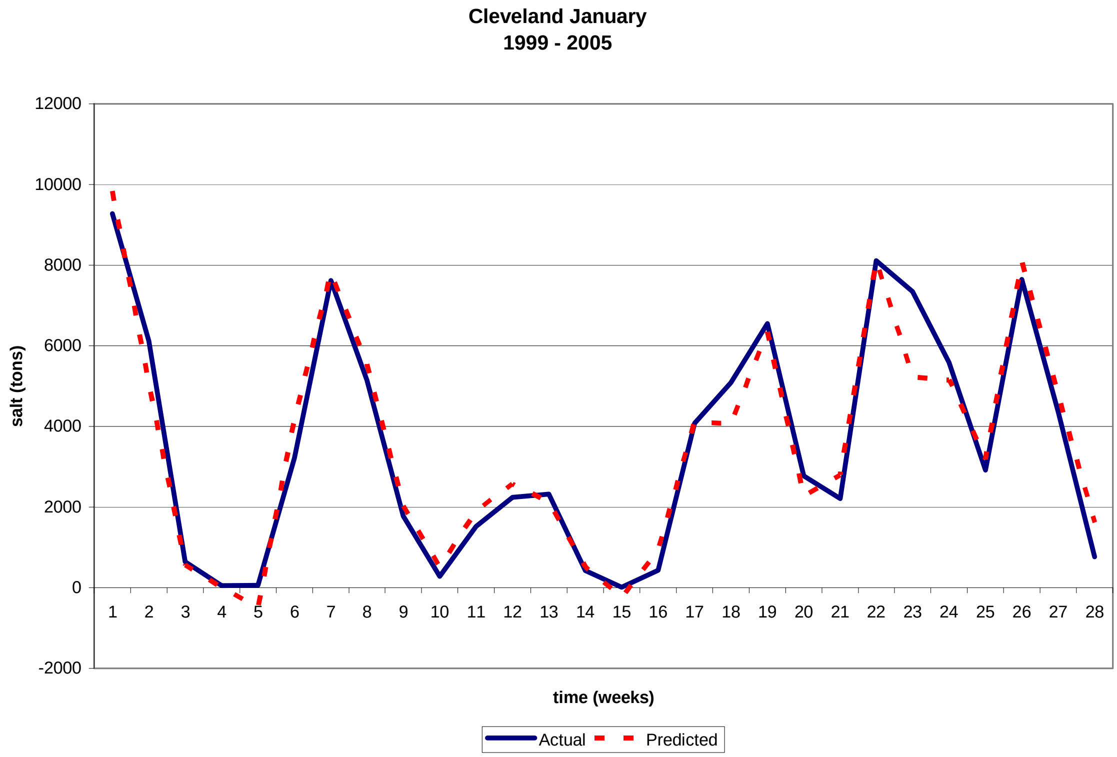



**Figure 4.7 - Cuyahoga January actual and predictd usage**

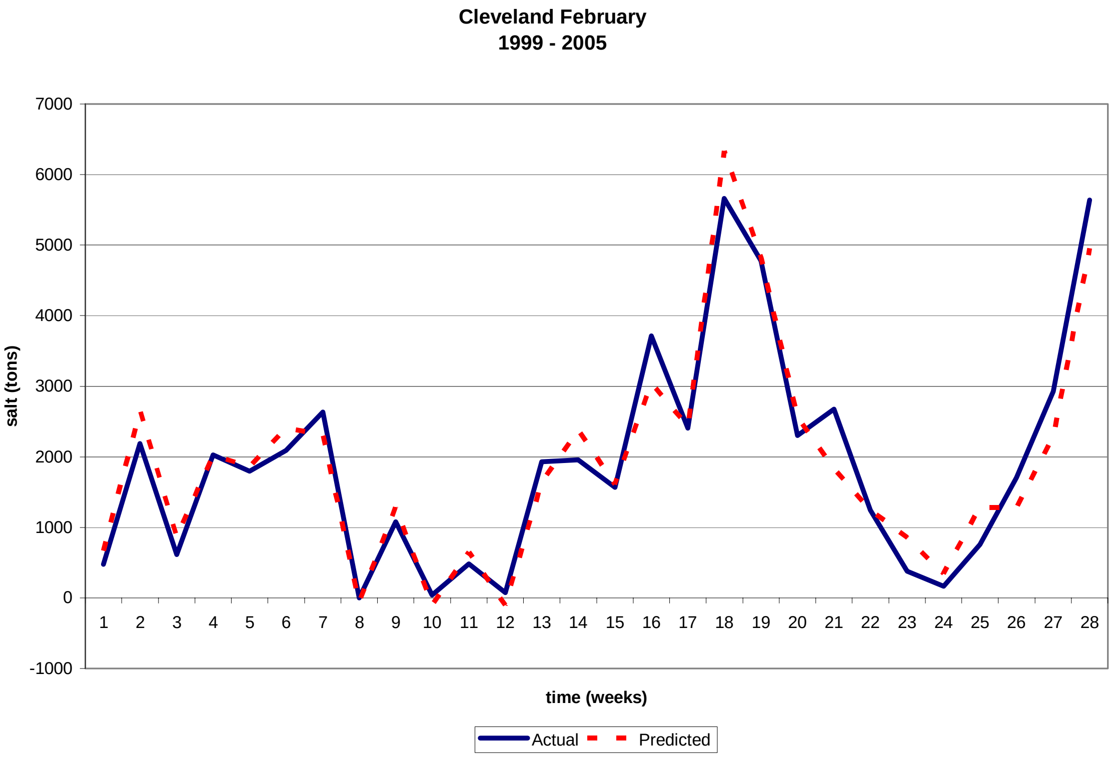



**Figure 4.8 - Cuyahoga February actual and predicted usage**

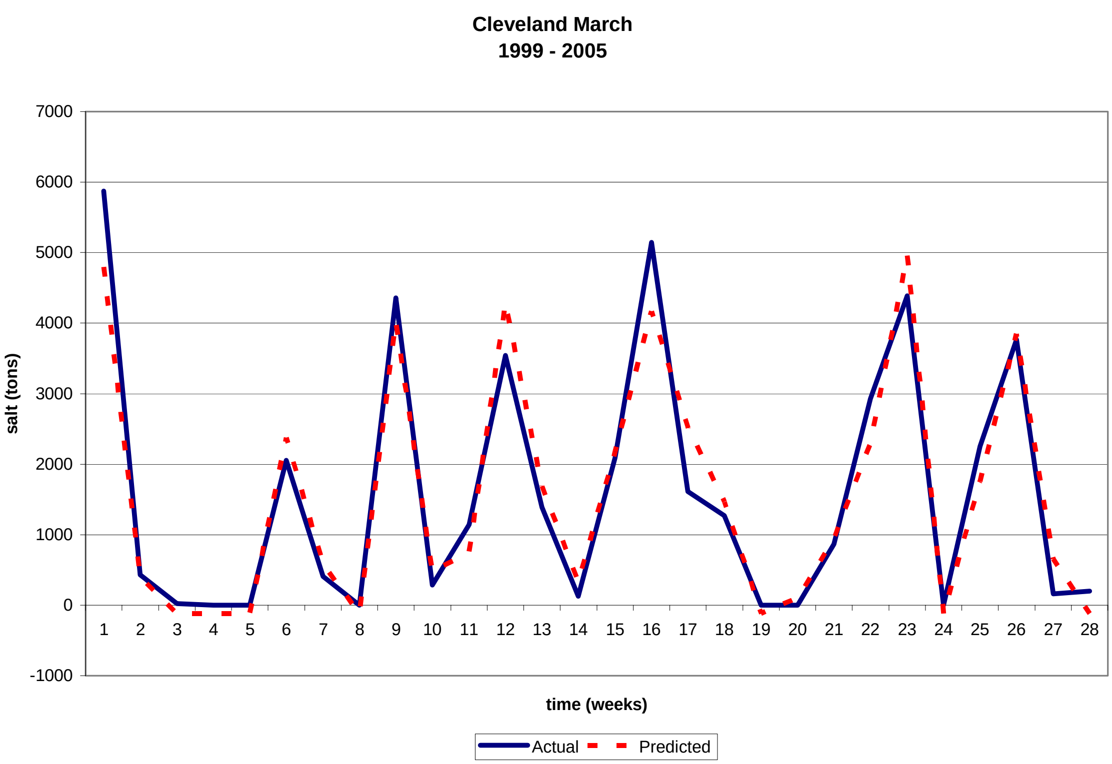



**Figure 4.9 - Cuyahoga March actual and predicted usage**

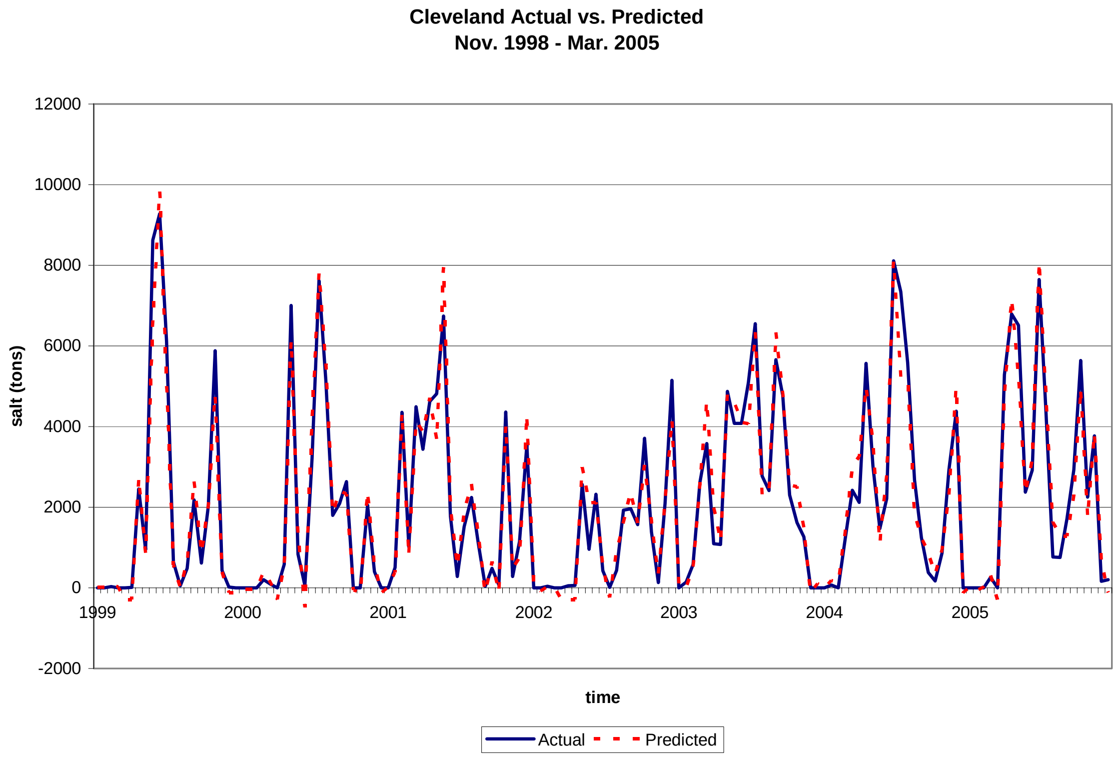



**Figure 4.10 - Cuyahoga November 1998 – March 2005 actual and predicted usage**

## 4.4. All other Ohio county models

Following the same methodology as described for deriving the Cuyahoga regression model, the other county models and variables were derived. These models are summarized in the following Tables. Recall that for each county, there is a unique regression model for predicting salt usage for each month of the winter season. The models are used for establishing the ($R$, $S$)-inventory guideline parameters and also to establish common climate zones so that only a few models may be used instead of one for each county.

**Table 4.4 - Summit County weather variables used for the model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >.001 | >.001 | X | X | >.001 | <30 | <30 | <30 | 0.999 | 0.999 | 92 |
| Dec. | >.001 | >.001 |  | X | >.001 |  | <32 |  | 0.900 | 0.883 | 118000 |
| Jan. | >0 | >0 | X | X |  | <30 |  |  | 0.889 | 0.863 | 174000 |
| Feb. | >.001 | >.001 | X | X |  |  |  |  | 0.808 | 0.775 | 109000 |
| Mar. | >.001 | >.001 | X | X |  | <30 | <30 | <30 | 0.955 | 0.939 | 52000 |

$Akron_{nov.}$ = .53351 + 215.49 * Sn + 4.2022 * DSn + 415.12 * FzR + 467.59 * BSn – 313.81 * SnC – 325.53 * MaxT + 2.0358 * MinT + 414.97 * AveT

$Akron_{dec.}$ = 202.78 + 154.25 * Sn + 275.54 * DSn + 269.73 * BSn + 42.934 * SnC – 56.003 * MinT

$Akron_{jan.}$ = -361.30 + 139.77 * Sn + 160.63 * DSn + 373.65 * FzR + 343.07 * BSn + 115.09 * MaxT

$Akron_{feb.}$ = 30.177 + 54.701 * Sn + 220.94 * DSn + 215.5578 * FzR + 349.6024 * BSn

$Akron_{mar.}$ = -88.541 + 189.23 * Sn + 61.050 * DSn + 196.78 * FzR + 201.025 * BSn - 244.27 * MaxT + 31.533 * MinT + 159.96 * AveT

**Table 4.5 – Mahoning County weather variables used for the model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >.001 | >.001 |  | X | >.001 | <32 | <32 |  | 0.986 | 0.982 | 3420 |
| Dec. | >.001 | >.001 | X |  |  | <32 |  |  | 0.794 | 0.766 | 289000 |
| Jan. |  | >.001 | X |  |  |  |  | <30 | 0.816 | 0.793 | 449000 |
| Feb. | >0 | >0 | X |  |  | <30 |  |  | 0.813 | 0.781 | 208000 |
| Mar. | >.001 | >.001 |  |  |  | <32 |  |  | 0.870 | 0.853 | 96300 |

$Youngstown_{nov.}$ = -21.192 – 128.16 * Sn + 115.88 * DSn + 133.65 * BSn + 370.89 * SnC + 326.02 * MaxT – 71.996 * AveT

$Youngstown_{dec.}$ = -179.64 + 168.72 * Sn + 138.06 * DSn + 456.86 * FzR + 98.163 * MaxT

$Youngstown_{jan.}$ = -863.40 + 445.09 * DSn + 412.86 * FzR + 172.64 * AveT

$Youngstown_{feb.}$ = 146.36 + 229.96 * Sn – 90.282 * DSn + 271.08 * FzR + 258.35 * MaxT

$Youngstown_{mar.}$ = -133.75 + 153.13 * Sn + 143.10 * DSn + 138.53 * MaxT

**Table 4.6 – Richland County weather variables used for the model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >.001 | >.001 | | | >.001 | <30 | <30 | <30 | 0.965 | 0.961 | 2100 |
| Dec. | >.001 | >.001 | X | | >.001 | <32 | <32 | | 0.893 | 0.870 | 52300 |
| Jan. | >.001 | >.001 | X | X | >.001 | | <32 | <32 | 0.936 | 0.913 | 33200 |
| Feb. | >0 | | | | >0 | | | | 0.721 | 0.698 | 72600 |
| Mar. | >0 | | X | | >0 | <32 | <32 | <32 | 0.951 | 0.937 | 12300 |

$$\text{Mansfield}_{nov.} = 13.061 + 34.572 * \text{Sn} + 18.642 * \text{DSn} + 221.86 * \text{SnC} + 73.480 * \text{MaxT} - 6.9498 * \text{MinT} - 80.086 * \text{AveT}$$

$$\text{Mansfield}_{dec.} = 88.824 + 102.90 * \text{Sn} + 59.474 * \text{DSn} + 255.67 * \text{FzR} - 37.844 * \text{SnC} + 114.87 * \text{MaxT} - 48.457 * \text{MinT}$$

$$\text{Mansfield}_{jan.} = 193.17 + 112.58 * \text{Sn} + 107.92 * \text{DSn} + 33.667 * \text{FzR} + 190.3237 * \text{BSn} + 19.778 * \text{SnC} - 111.50 * \text{MinT} + 100.69 * \text{AveT}$$

$$\text{Mansfield}_{feb.} = -28.325 + 149.37 * \text{Sn} + 53.925 * \text{SnC}$$

$$\text{Mansfield}_{mar.} = 47.285 + 152.81 * \text{Sn} + 101.44 * \text{FzR} + 49.478 * \text{SnC} - 112.78 * \text{MaxT} - 27.039 * \text{MinT} + 25.443 * \text{AveT}$$

**Table 4.7 - Franklin County weather variables used for the model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >0 | >0 | X | | >0 | <30 | <30 | <30 | 0.997 | 0.996 | 250 |
| Dec. | >.001 | | X | X | >.001 | <30 | | <30 | 0.830 | 0.794 | 267000 |
| Jan. | | | X | X | >.001 | | <32 | <32 | 0.800 | 0.755 | 798000 |
| Feb. | >.001 | >.001 | | X | | | <32 | <32 | 0.898 | 0.875 | 256000 |
| Mar. | | >.001 | X | X | >.001 | <30 | | <30 | 0.963 | 0.952 | 16100 |

$$\text{Columbus}_{nov.} = -1.0374 + 447.39 * \text{Sn} - 17.789 * \text{DSn} - 107.70 * \text{FzR} + 52.755 * \text{SnC} + 146.25 * \text{MaxT} + 4.8905 * \text{MinT} - 145.90 * \text{AveT}$$

$$\text{Columbus}_{dec.} = 41.512 + 369.81 * \text{Sn} + 544.66 * \text{FzR} - 500.04 * \text{BSn} + 283.47 * \text{SnC} - 193.11 * \text{MaxT} + 85.684 * \text{AveT}$$

$$\text{Columbus}_{jan.} = -219.51 + 375.44 * \text{FzR} + 897.85 * \text{BSn} + 97.509 * \text{SnC} - 164.52 * \text{MaxT} + 404.06 * \text{AveT}$$

$$\text{Columbus}_{feb.} = -745.30 + 140.13 * \text{Sn} + 279.64 * \text{DSn} + 530.55 * \text{BSn} + 101.33 * \text{MinT} + 85.084 * \text{AveT}$$

$$\text{Columbus}_{mar.} = -39.788 + 368.54 * \text{DSn} + 561.45 * \text{FzR} - 444.92 * \text{BSn} - 100.96 * \text{SnC} - 194.02 * \text{MaxT} + 129.66 * \text{AveT}$$

**Table 4.8 - Montgomery County weather variables used for the model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >.001 | >.001 | | | >.001 | <30 | <30 | <30 | 0.798 | 0.741 | 91 |
| Dec. | | >0 | X | X | >0 | <30 | | | 0.905 | 0.888 | 8608 |
| Jan. | | >.001 | X | X | | | | | 0.890 | 0.876 | 28683 |
| Feb. | >0 | >0 | | X | | <30 | | | 0.927 | 0.914 | 3382 |
| Mar. | >0 | | X | | | | | | 0.808 | 0.792 | 1388 |

$$\text{Dayton}_{nov.} = -3.7195 - 114.69 * \text{Sn} + 70.823 * \text{DSn} + 56.501 * \text{MaxT} + 2.0258 * \text{MinT} - 22.321 * \text{AveT}$$

$$\text{Dayton}_{dec.} = -16.280 * \text{Sn} + 8.6404 * \text{DSn} + 43.812 * \text{FzR} + 201.16 * \text{BSn} + 54.4979 * \text{SnC} + 16.662 * \text{MaxT}$$

$$\text{Dayton}_{jan.} = -80.239 + 236.64 * \text{DSn} + 162.31 * \text{FzR} + 235.13 * \text{BSn}$$

$$\text{Dayton}_{feb.} = -25.156 + 36.839 * \text{Sn} + 18.063 * \text{DSn} + 95.344 * \text{BSn} + 19.08488 * \text{MaxT}$$

$$\text{Dayton}_{mar.} = 6.2882 + 31.099 * \text{Sn} + 68.448 * \text{FzR}$$

**Table 4.9 - Hamilton County weather variable used for the model**

| Month | Sn | DSn | FzR | BSn | SnC | MaxT | MinT | AveT | $R^2$ | $R^2$ Adj. | MSE |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Nov. | >.001 | >.001 | | | >.001 | <32 | | <32 | 1.000 | 1.000 | 0 |
| Dec. | >.001 | >.001 | | | >.001 | <32 | | | 0.875 | 0.858 | 108000 |
| Jan. | >0 | | X | X | >0 | <30 | | <30 | 0.852 | 0.810 | 175000 |
| Feb. | >0 | >0 | X | X | >0 | <30 | | <30 | 0.934 | 0.911 | 29200 |
| Mar. | >0 | >0 | | | >0 | | <30 | <30 | 0.814 | 0.771 | 16300 |

$$\text{Cincinnati}_{nov.} = .02158 - 141.02 * \text{Sn} + 56.387 * \text{DSn} + 288.04 * \text{SnC} + 2.5329 * \text{MaxT} - .59115 * \text{AveT}$$

$$\text{Cincinnati}_{dec.} = 11.066 + 118.05 * \text{Sn} + 197.49 * \text{DSn} + 199.27 * \text{SnC} - 48.380 * \text{MaxT}$$

$$\text{Cincinnati}_{jan.} = -82.383 + 199.76 * \text{Sn} + 328.30 * \text{FzR} + 682.66 * \text{BSn} + 56.408 * \text{SnC} + 132.39 * \text{MaxT} + 28.480 * \text{AveT}$$

$$\text{Cincinnati}_{feb.} = 41.060 + 159.64 * \text{Sn} - 63.126 * \text{DSn} + 331.67 * \text{FzR} - 297.84 * \text{BSn} + 61.645 * \text{SnC} + 99.907 * \text{MaxT} + 47.958 * \text{AveT}$$

$$\text{Cincinnati}_{mar.} = -77.602 + 71.422 * \text{Sn} + 109.15 * \text{DSn} + 44.482 * \text{SnC} + 30.508 * \text{MinT} - 112.79 * \text{AveT}$$

No regression model for Toledo was developed due to the inaccurate weather data from Toledo and the lack of fit of the regression model with the use of the weather data from the Detroit airport. The (*R*, *S*)-inventory guideline for Toledo was constructed directly utilizing the historical salt usage data for these calculations and is studied more thoroughly.

## 4.5. Models based on climate zones in Ohio

There are 88 counties in Ohio. Based on the procedure in the preceding analysis there would need to be 88 separate weather regression models to use to predict salt usage in each county. To lower the volume of data and effort required to develop and maintain the models one model could be used for counties that are in the same region of the state. This is based on the assumption that the salt usage model is driven by a combination of weather characteristics, and how local guidelines and conditions respond to the weather. The weather regression model is used to calculate predicted values for the calculation of the (*R*, *S*)-inventory guideline. The method to test for these regional models is to: 1. accumulate the relevant weather variables for the new county, and 2. insert them into a weather regression model of a nearby county. This will result in predictions for the new county based on the regression parameters from the nearby county. These predictions will ultimately be used in the (*R*, *S*) calculations.

Three counties were studied to see if the models created for use in that representative county can be used in another county. Table 4.10 lists the different scenarios tested.

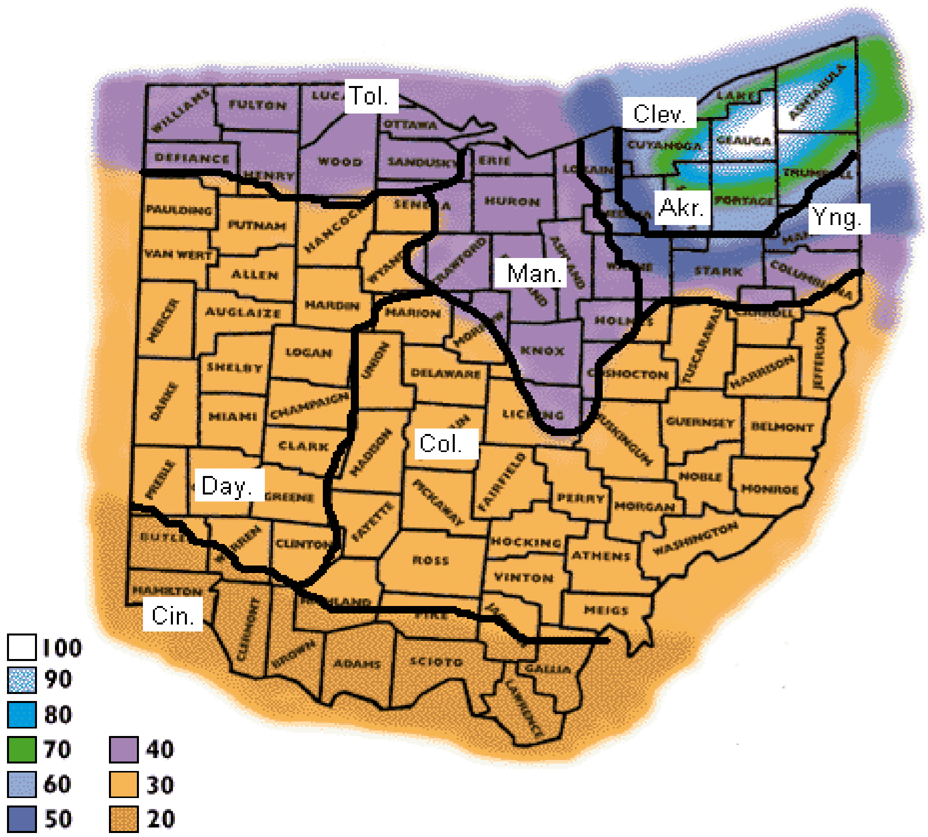
**Table 4.10 - Regression scenarios tested**

| County | Scenario # | Scenarios |
|---|---|---|
| Summit | 1 | Summit weather model with Summit weather data |
| | 2 | Cuyahoga weather model with Summit weather data taking into account percent difference in lane miles |
| | 3 | Mahoning weather model with Summit weather data taking into account percent difference in lane miles |
| Cuyahoga | 4 | Cuyahoga weather model with Cuyahoga weather data |
| | 5 | Summity weather model with Cuyahoga weather data taking into account percent difference in lane miles |
| | 6 | Mahoning weather model with Cuyahoga weather data taking into account percent difference in lane miles |
| Mahoning | 7 | Mahoning weather model with Mahoning weather data |
| | 8 | Summit weather model with Mahoning weather data taking into account percent difference in lane miles |
| | 9 | Cuyahoga weather model with Mahoning weather data taking into account percent difference in lane miles |

The three counties are in the northeast part of Ohio, in and around the “lake effect” snow belt. The process consists of taking the weather regression model parameters originally developed for Akron (Summit County), Cleveland (Cuyahoga County), and Youngstown (Mahoning County) and applying each to a different county’s weather data. The predictions from the nearby county’s model were compared to the predictions from the local model. Because all counties do not have the same amount of lane miles and assuming that usage is close to linear in lane-miles, a lane mileage conversion is used. Based on an internal ODOT document Cuyahoga has a total of 1990 miles, Summit has 965 lane miles, and Mahoning has 722 miles. The lane mileage conversion generates a predicted value of salt usage found from the model and then divides by the number of lane mileage of the original county. This predicts the spread rate of salt per lane mile. This number can then be multiplied by the lane mileage of the intended county for predicted salt usage in the intended county.

From the comparisons it was found that the temperature and snowfall variations used in defining the original model for the original county must also be used for the new county. For example if the model created for Cuyahoga was created using the variables "temperature < 30° F" and "snowfall > .001 inches", then when the model is used for Summit County the same variables must be included. It is also important to use the lane mileage adjustment for the predictions of salt usage when using a model developed for another city/county. A third finding is that models are only accurate when used in other counties with smaller lane mileage. This was found through comparing mean squared errors. These comparisons are listed in Table 4.11, where Cuyahoga has the largest number of lane miles followed by Summit and then Mahoning. For example a model created for Summit is not appropriate to predict salt for Cuyahoga County (a large lane-mile county) even with the lane mileage conversions. The result of using Summit County for predictions in Cuyahoga County is an extreme under prediction. Finally, from the comparisons it was found that the models developed directly for a county using local weather and usage data work the best, but utilizing a larger county's weather regression model on a smaller county in a similar weather zone also performs well. For example all models predict well in all months when a spike or a drop in usage occurs. That is the predictions follow the same pattern. They might over or under predict, but they perform very well in predicting the trend. This leads to the belief that weather regression models developed for one county in a similar weather zone can be used for other counties in the same zone. A rough description of the weather zones are shown in the map of Ohio in Figure 4.11. Figure 4.11 was constructed from the average annual snowfall graph from Ohio Department of Transportation web site and lines were added to identify the weather zones.

**Figure 4.11 – Map of Ohio with climate zones**




Specifically it was found that Cleveland and Akron are in similar weather climates and that the model created for Cleveland can be used for Akron. This was determined by comparing the mean squared errors of the three alternatives: Cuyahoga's model used on Summit County, Mahoning model used on Summit, and the use of Summit's model. The results of the mean squared errors of the predictions are shown in Table 4.11.

**Table 4.11 - Mean squared error for regression scenarios**

| | Mean Square Errors | | | | |
|---|---|---|---|---|---|
| Scenario | November | December | January | February | March |
| 1 | 91.6 | 118000 | 174000 | 109000 | 50200 |
| 2 | 54000 | 238000 | 513000 | 175000 | 153000 |
| 3 | 517000 | 408000 | 1110000 | 302000 | 178000 |
| 4 | 10200 | 561000 | 461000 | 200000 | 277000 |
| 5 | 285000 | n/a | 1270000 | n/a | n/a |
| 6 | 511000 | n/a | 3090000 | n/a | n/a |
| 7 | 3420 | 288000 | 449000 | 208000 | 107000 |
| 8 | 82600 | 455000 | 1040000 | 561000 | 202000 |
| 9 | 46400 | 396000 | 1410000 | 724000 | 318000 |

In summary, the use of the Summit County model is the best performer, but using the Cuyahoga County model on the Summit data performs adequately. The model created for Mahoning and used on Summit did not perform as well. This fact reinforces the finding that models from counties with fewer lane miles do not perform well when used on larger counties even when taking into account the lane miles. Figure 4.12 compares the actual usage with the predictions from Akron using the Akron model and using the Cleveland model during the month of November. From Figure 4.12 it is hard to see the Akron predictions because the predictions are so close to the actual numbers, but the graph for the Cleveland model compared to the actual usage shows just how accurately the model predicts the spikes in demands. Figure 4.13 compares the model predictions vs the actuals for all November weeks for each year over the 7 years in our data.

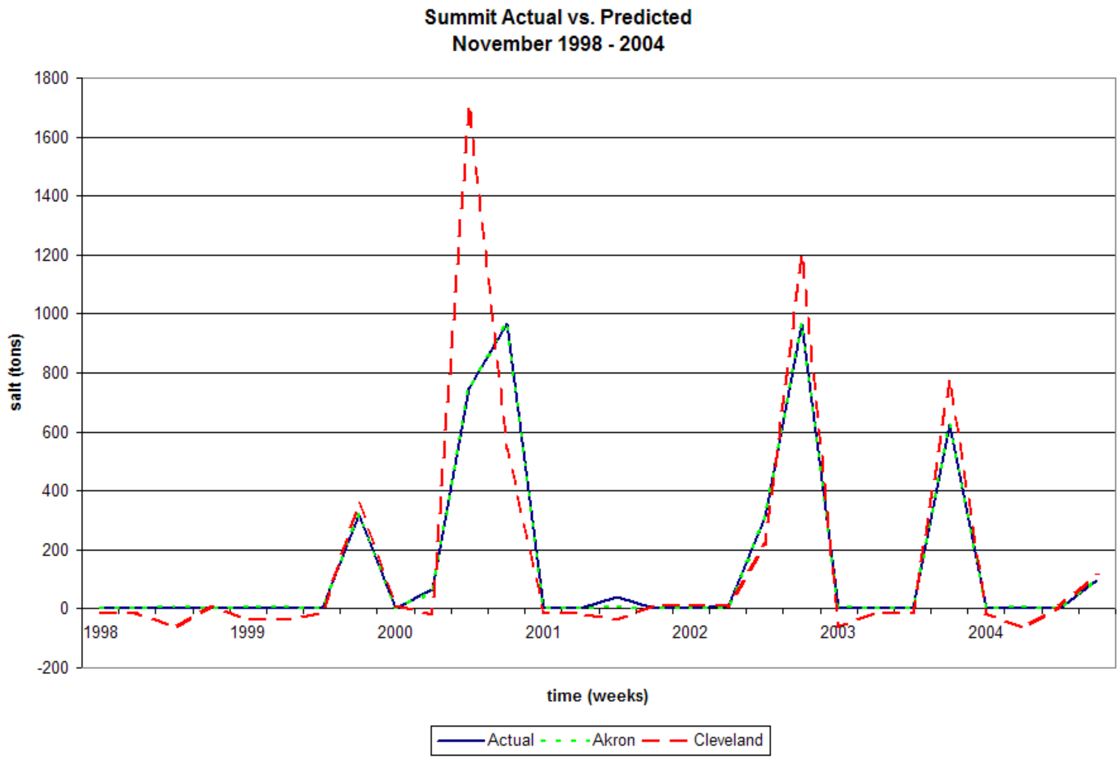



**Figure 4.12 - Actual vs. predicted for Summit County in November**

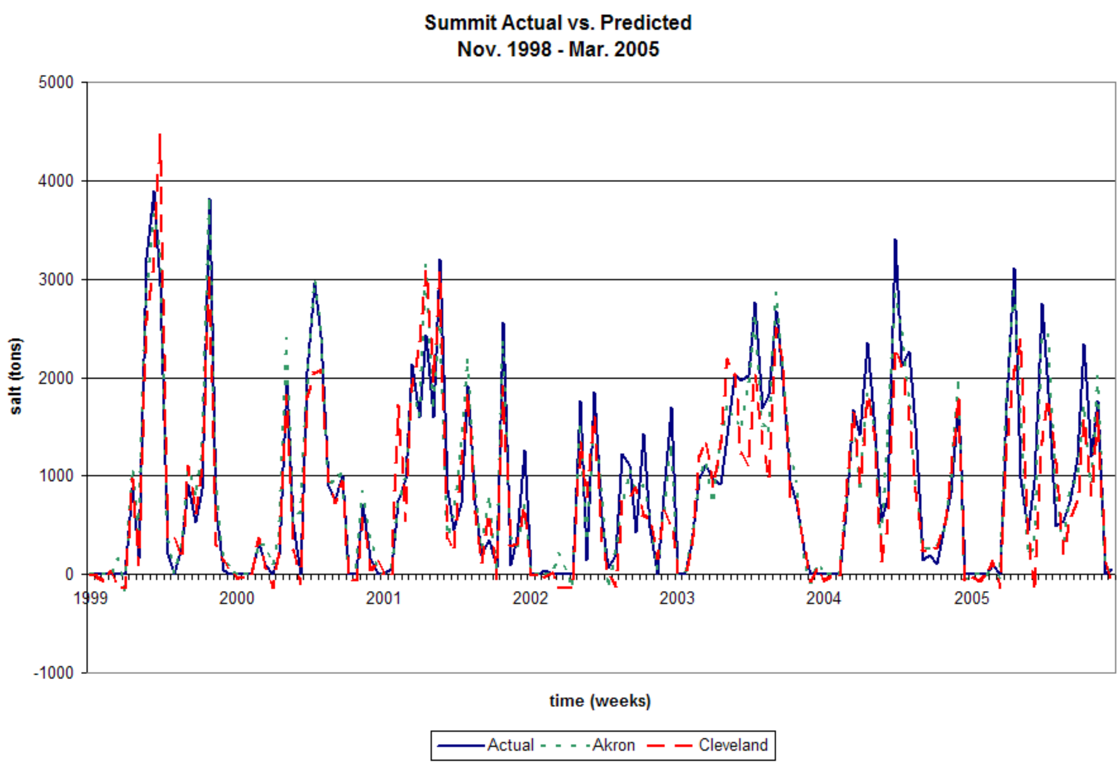



**Figure 4.13 - Actual vs. predicted for Summit County for 7 years**

# 5. The (*R*, *S*)-Inventory Guideline

This chapter provides the details of calculating the parameters of the (*R*, *S*)-inventory guideline as described by Roelants and Muyldermans (2002). The parameters are calculated by taking the predictions of salt usage from the weather regression models for all counties found in chapter 4 and finding the mean usage during the lead time and the representative standard deviations. These numbers can also be calculated simply by taking the historical data and performing the same calculations. The historical usage data can be used to calculate the (*R*, *S*)-inventory guideline if relevant weather data is not available. This approach based on only the historical usage data will be shown for Lucas County (Toledo) for which no weather regression model was calculated.

## 5.1. The (*R*, *S*)-inventory guideline calculations

The (*R*, *S*)-inventory guideline parameters are calculated by finding the mean and standard deviation of the weekly salt usage prediction values for each month which were calculated from the weather regression models. The data was already accumulated into weeks and the delivery lead time is also one week. A service level of 99.8% is used for the calculation of the safety stock and thus $k$ in equation (2) is 2.88 and the safety stock equation is: $ss = 2.88\sigma_{LT}$. The mean usage during the lead time ($\mu_{LT}$) (which is the expected weekly demand) is found by taking the mean of the weekly data collected from each month. The reorder point (*R*) is calculated by equation (1). The target level (*S*) is found by equation (3). The inventory guideline parameters for all the counties are presented in the following sections with the calculations of the safety stock ($ss$), the reorder point (*R*), and the target level (*S*).

## 5.2. The (*R*, *S*)-inventory guideline values for Cuyahoga County

This section provides the details of the results for the county of Cuyahoga. The final results for the guidelines of all the other counties are presented without detailed explanation. Table 5.1 shows the safety stock for Cuyahoga calculated by taking the standard deviation of the predictions for each month, and multiplied by 2.88 which equates to a 99.8% safety level. The safety stock is the amount of inventory to be held in case of uncertainties in demand, such as a severe storm that would cause a spike in usage above the average. Table 5.1 also shows the mean or expected usage during the lead time. Finally Table 5.1 provides the point at which the county will reorder (*R*) during each month and also the target level for inventories for each month. The target level (*S*) is used to determine the amount to order, which is the target level minus current inventory level. Equation (4) displays the equation for the amount to be ordered (*Q*). The equation is the target level (*S*) minus the current inventory level (*I*), which is calculated when current inventory (*I*) is less then the reorder point (*R*).

$$Q = S - I \tag{4}$$

For example in the month of December, when inventory, I, drops to or below 9700 tons of salt, (12,600 – I) tons of salt is ordered.

**Table 5.1 - (*R*, *S*)-inventory guideline values for Cuyahoga County**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 2750 | 6930 | 8080 | 4370 | 4920 |
| 2 | $\mu_{LT}$ | 395 | 2820 | 3520 | 1900 | 1560 |
| 3 = 1 + 2 | R | 3140 | 9750 | 11600 | 6280 | 6490 |
| 4 | E(week) | 395 | 2820 | 3520 | 1900 | 1560 |
| 5 = 3 + 4 | S | 3540 | 12600 | 15100 | 8180 | 8050 |

## 5.3. The (*R*, *S*)-inventory guideline values for Summit County

In section 4.5, two regression models for Summit County were proposed, and these were used to develop two (*R*, *S*)-inventory guidelines. It was found from comparisons between mean squared errors of using the Summit weather regression model for Summit and the Cuyahoga regression model for Summit that these models were both acceptable. The regression model only predicts salt usage, but these values are then used to derive the (*R*, *S*)-inventory guideline. Table 5.2 and Table 5.3 show the results for Summit based on the two models.

**Table 5.2 - (*R*, *S*)-inventory guideline values for Summit using the Summit model**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 863 | 2750 | 3060 | 1800 | 2580 |
| 2 | $\mu_{LT}$ | 149 | 1150 | 1580 | 889 | 707 |
| 3 = 1 + 2 | R | 1010 | 3900 | 4640 | 2690 | 3290 |
| 4 | E(week) | 149 | 1150 | 1580 | 889 | 707 |
| 5 = 3 + 4 | S | 1160 | 5040 | 6220 | 3580 | 3990 |

**Table 5.3 - (*R*, *S*)-inventory guideline values for Summit using the Cuyahoga model**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 1200 | 2920 | 3080 | 1680 | 2100 |
| 2 | $\mu_{LT}$ | 163 | 1130 | 1280 | 743 | 573 |
| 3 = 1 + 2 | R | 1370 | 4050 | 4360 | 2430 | 2670 |
| 4 | E(week) | 163 | 1130 | 1280 | 743 | 573 |
| 5 = 3 + 4 | S | 1530 | 5170 | 5630 | 3170 | 3240 |

Comparing Tables 5.2 and 5.3, it is evident that all the safety stocks with the exception of February and March are higher with use of the Cuyahoga model. These values are an indication that the weather in the area is very unpredictable and more safety stock is required to prevent a salt stockout. The values are relatively close with the maximum percent difference of 35.6% for the reorder point and 31.9% for the stock target level in the month of November. The average percent difference is .986% and -1.06% for the reorder point and stock target level respectively. There is some concern with the values for January, February, and March because the distance between these two values represent the frequency and the amount of orders. The reorder points and the stock target levels which depict the amount to order for these months are somewhat low as in Table 5.3. To answer the question as to how well the two models perform when implemented, a simulation model is used in Chapter 6 to test the performance of the guidelines in a more realistic setting.

## 5.4. The (*R*, *S*)-inventory guideline values for Lucas County

(*R*, *S*) guideline parameters for Lucas County (Toledo) were calculated similarly, but rather than using predictions based on the weather regression model the parameters were calculated using the historical weather data. The calculation of the mean and standard deviation which drive the (*R*, *S*)-inventory guideline were found from the 1998-2005 data of salt usage in Lucas. For all of the other counties the (*R*, *S*)-inventory guidelines based directly on historical usage data are shown in the appendix, sorted by district.

**Table 5.4 - (*R*, *S*)-inventory guideline values for Lucas County**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 78.8 | 1000 | 1070 | 600 | 669 |
| 2 | $\mu_{LT}$ | 9.31 | 292 | 315 | 162 | 140 |
| 3 = 1 + 2 | R | 88.1 | 1290 | 1380 | 762 | 808 |
| 4 | E(week) | 9.31 | 292 | 315 | 162 | 140 |
| 5 = 3 + 4 | S | 97.4 | 1590 | 1700 | 925 | 948 |

## 5.5. The (*R*, *S*)-inventory guideline values for the remaining counties

Table 5.5 through Table 5.9 list the (*R*, *S*)-inventory guideline parameters for the other counties containing a major city using the predictions for each county found from the weather regression models.

**Table 5.5 - (*R*, *S*)-inventory guideline values for Mahoning County**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 1260 | 2850 | 3830 | 2530 | 2180 |
| 2 | $\mu_{LT}$ | 198 | 1190 | 1910 | 1100 | 604 |
| 3 = 1 + 2 | R | 1460 | 4040 | 5740 | 3630 | 2790 |
| 4 | E(week) | 198 | 1190 | 1910 | 1100 | 604 |
| 5 = 3 + 4 | S | 1660 | 5230 | 7650 | 4730 | 3390 |

**Table 5.6 - (*R*, *S*)-inventory guideline values for Richland County**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 656 | 1730 | 1720 | 1200 | 1250 |
| 2 | $\mu_{LT}$ | 99.6 | 650 | 845 | 546 | 287 |
| 3 = 1 + 2 | R | 756 | 2380 | 2570 | 1750 | 1530 |
| 4 | E(week) | 99.6 | 650 | 845 | 546 | 287 |
| 5 = 3 + 4 | S | 855 | 3030 | 3410 | 2290 | 1820 |

**Table 5.7 - (*R*, *S*)-inventory guideline values for Franklin County**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 738 | 2990 | 4650 | 3900 | 1630 |
| 2 | $\mu_{LT}$ | 82.7 | 960 | 1950 | 908 | 360 |
| 3 = 1 + 2 | R | 821 | 3950 | 6610 | 4810 | 1990 |
| 4 | E(week) | 82.7 | 960 | 1950 | 908 | 360 |
| 5 = 3 + 4 | S | 904 | 4910 | 8560 | 5720 | 2350 |

**Table 5.8 - (*R*, *S*)-inventory guideline values for Montgomery County**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 47.9 | 760 | 1310 | 550 | 214 |
| 2 | $\mu_{LT}$ | 5.91 | 173 | 377 | 110 | 42.6 |
| 3 = 1 + 2 | R | 53.8 | 932 | 1680 | 660 | 257 |
| 4 | E(week) | 5.91 | 173 | 377 | 110 | 42.6 |
| 5 = 3 + 4 | S | 59.8 | 1110 | 2060 | 770 | 299 |

**Table 5.9 - (*R*, *S*)-inventory guideline values for Hamilton County**

| Months | | Nov | Dec | Jan | Feb | Mar |
|---|---|---|---|---|---|---|
| 1 | SS | 288 | 2350 | 2550 | 1600 | 708 |
| 2 | $\mu_{LT}$ | 21.9 | 627 | 1010 | 351 | 155 |
| 3 = 1 + 2 | R | 310 | 2980 | 3560 | 1950 | 863 |
| 4 | E(week) | 21.9 | 627 | 1010 | 351 | 155 |
| 5 = 3 + 4 | S | 332 | 3600 | 4570 | 2300 | 1020 |

## 5.6. Study of correlation variables

In the classical models of statistics, including regression models, independence of data is an important property for the models to be effective. As defined by Montgomery and Runger (2003) correlation is the study of the linear relationship between variables. We considered variables to be independent if the correlation between them is zero. The higher the correlation the stronger the linear dependence between two variables. In this case the variables are the usage of salt on two different days, or in two different regions of a county.

In the inventory model based on an ($R$, $S$) guideline, salt usage in each period is considered to be independent and normally distributed when developing the safety stock values. The usage in each county in the model was computed by accumulating data from all the garages within the county. This is of particular importance because the usages on a given day from the different garages of a county are not independent of each other. It may happen that one side of a county may get more snow then the other, but if it snows often all areas of the county will see snow. By formulating a county model the correlation between garages is combined in the county model.

The second source of correlation is between daily reported salt usages on two adjacent days. The models were constructed by accumulating the salt usage for a week instead of by day. By developing the models in this way the correlation between nearby (weekly) data points is reduced. We studied this auto-correlation through a small comparison. The study covered Cuyahoga County from November 2004 until March 2005. Taking daily salt usage data and looking at correlation between adjacent days, autocorrelation is .705. For a distance of 2 days, the autocorrelation in daily usage is .687. A distance of one will study the correlation between adjacent data points in the usage data; while a distance of two will study data points separated by two data points. This level of correlation is not surprising given that snow on one day often affects the amount of salt used over several days. By taking the data and then collecting them into weeks (by summing total usage during the week) the correlation is drastically reduced to .478 for a distance of one week and -.011 for a distance of two weeks. The results are very similar for the autocorrelation of the weekly predicted values (from the regression model) with the lag one equaling .443 and a lag of 2 equating to -.006. Even in a county that uses very little salt such as Montgomery County (Dayton) the autocorrelation of the weekly data for the same time period with a lag of 1 is .085 and a lag 2 of -.220. As a result the data points used to build the weather regression model and thus the ($R$, $S$)-inventory guideline have reasonably low correlation and look to be independent. Also, it is worthwhile to note that combining together 7 daily demands and multiple garage locations will improve the "normality" of the weekly usage. Further impacts of these assumptions on the performance of the guidelines are evaluated using a simulation approach in the next chapter.

# 6. The Simulation Model

This chapter provides a detailed study of the performance of the (*R*, *S*)-inventory guidelines using an Arena simulation. This chapter consists of four sections. The first section gives insight into the model developed to simulate a realistic implementation of the guideline. The subsequent sections give simulation results for 3 counties. First, we studied the effects of implementing the guideline in Cuyahoga County using actual usage from 1998 – 2005. Results for Lucas County will study the effects of any collaborative effects of calculating the (*R*, *S*)-inventory guideline county wide. Finally, we studied whether a model originally developed for one county can be used effectively in another county. This will be studied using Summit County.

## 6.1. Simulation development

A simulation model was constructed to study the effects of implementing the (*R*, *S*)-inventory guideline in a realistic setting. The simulation is driven by actual historical salt usage data. A simulation is a good way of studying a real life condition by allowing experiments with the model as compared to experiments in a real world situation. The goals of the simulation study are:

1. Test the actual performance of the suggested (*R*, *S*) guidelines vs. the predicted performance in terms of service level.

2. Compare the suggested (*R*, *S*) guidelines to current practice and identify any factors that have not been considered in the design.

3. From the salt vendor perspective compare the stream of orders generated by the current practice and the orders generated by the (*R*, *S*) guideline.

One of the important differences between the (*R*, *S*) guideline and the current practice, is that in current practice the goal is to keep the garage storage capacity as close to full as possible at all times, including at the beginning and end of the season. The simulation is used to compare the two approaches from the perspective of inventory levels and service level. The simulation model reads actual salt usage data and then applies the ordering logic of either the (*R*, *S*) guideline parameters or other guidelines. Figure 6.1 shows the structure of the model with the flow of salt from the vendor to the garage and eventual demand.

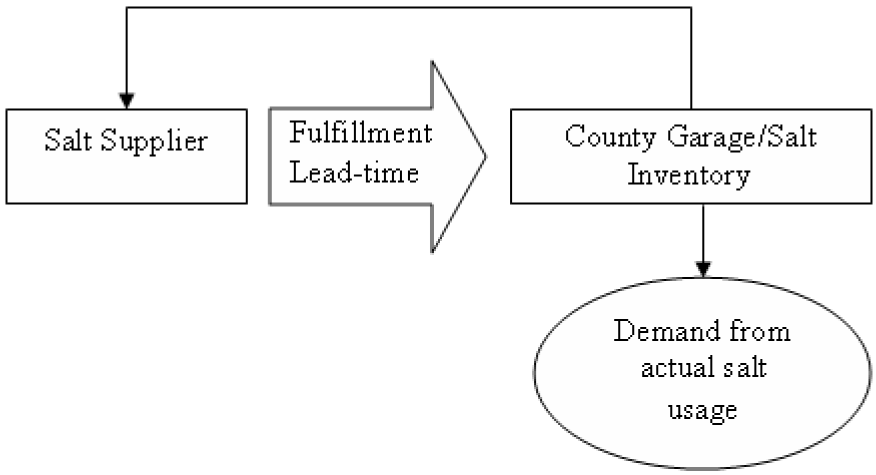



**Figure 6.1 – Salt order fulfillment and usage flow diagram**

In the model there is a delay of two days from the placement of an order by the county garage until the order can begin to be fulfilled. To determine the fulfillment lead time, the order is partitioned into a number of daily deliveries based on the history of actual received amounts for that county. A distribution is fit to the actual delivered data and is used to drive the fulfillment process in the model. A rough estimate on the number of days an order takes to fully deliver is to take the full order amount and divide by the maximum that can be received each day and add two days. From the actual state contracts with the suppliers, orders must be filled within 7 days. In reality the time to completely fulfill an order is dependent on many factors, including the availability of trucks and the availability of resources at the county garages to receive the salt. Because of these complicating factors it is important to model deliveries to the county garage with an appropriate level of detail. Because of the use of probability distribution to drive the rate of delivery for an order, the simulation creates some scenarios where deliveries are delayed beyond the 7-day contract guideline. These simulated scenarios stress the guidelines, in some cases beyond what has been experienced historically. These cases help determine which guidelines deal with both situations that have existed in the past, as well as new, worst-case scenario situations, where usage is very high, and replenishment is slower than expected.

The order streams from the simulation can be directly compared with actual order amounts. The level of inventory from the simulation can be compared to the actual level of the inventory observed in the years of the historical demand. The data for the actual inventory levels is computed with actual received, used, and beginning inventories. The simulation model is used for these computations, although the computations could be done directly using the data to generate results in the same format.

To study variations in the computed (*R*, *S*) guidelines that match some of the guidelines used in practice, the following initial conditions and guideline variations were considered for November, December, and January.

Initial inventory on November 1st:

i. Inventory reported in ODOT database for Nov. 1

ii. Target level (S) from (*R*, *S*) guideline for November

iii. Target level (S) from (*R*, *S*) guideline for March

iv. Target level (S) from (*R*, *S*) guideline for December

v. Target level (S) from (*R*, *S*) guideline for January

The initial inventories for the (*R*, *S*) guidelines were varied in this way to test the (*R*, *S*) guidelines directly and also to test the variations possible when the guideline is implemented.

Guideline variations for the five months of the study are:

i. Guideline computed in Section 4.2 for all months

ii. The guideline computed from Section 4.2 is used, but the guideline begins a number of days in the preceding month for December, January, February and March.

iii. The guideline computed from Section 4.2 is used, but the guideline begins a number of days in the preceding month for December and January only.

The guidelines were varied in this way because the simulation showed that large orders were made when changing from one month's guideline to the next month. This was the case especially when going from a lower reorder point and stock target level to one that is higher. As a result it would take up to one week for a garage to reach its stock target level for that month. By beginning months seven days into the preceding month a month would start off with close to its stock target level. The guidelines for the months of the study were varied to mimic the very conservative guidelines currently followed in practice. The most conservative guideline uses the January inventory target level for the beginning inventories for November and uses the January reorder point and target level for part of the month of December and all of January. This is conservative because January is the highest usage month historically.

The simulation was first used to study Cuyahoga County one of the very high usage counties in the "lake effect" region. It was run using data for all seven winter seasons starting with November 1998 –

March 1999 and for all years up until March 2005. Each year was run independently with results tabulated as averages. These variations on the (*R*, *S*) guidelines will be compared with the computed inventories from the actual used and received amounts. By utilizing not only the actual used amounts and received amounts the simulation could help compare the effectiveness of the (*R*, *S*)-inventory guideline parameters.

Three counties were considered in the simulation experiments: Cuyahoga, Lucas, and Summit. Although there are 5 garages/domes located in Cuyahoga the county was treated as a single inventory location because data for each individual garage was unavailable. Lucas County, which contains the City of Toledo, only contains one garage. Comparing results from Cuyahoga and Lucas allowed us to identify any differences in results for single and multiple location counties. Also, since Lucas County's (*R*, *S*) guideline was calculated strictly from historical data, the simulation could identify the effectiveness of calculating the guideline in this way. Finally, because two (*R*, *S*)-inventory polices were developed for Summit County in Section 4.3 using two different weather regression models, the effectiveness of each was studied. The two models for Summit were calculated by using the Summit weather regression model on Summit and then the Cuyahoga weather regression model used on Summit to calculate predicted salt usage. These predictions were then used to calculate individual (*R*, *S*)-inventory guideline parameters for Summit.

The variations shown in Tables 5.2 and 5.3 were compared to base schedule shown in Table 5.1:

**Table 6.1 - Schedule A (*R, S*) variations**

| Schedule A | |
|---|---|
| Month | Schedule |
| November guideline | November 1st to November 30th |
| December guideline | December 1st to December 31st |
| January guideline | January 1st to January 31st |
| February guideline | February 1st to February 28th |
| March guideline | March 1st to March 31st |

To effectively deal with up to one week of delivery lead time, the monthly (*R*, *S*) guidelines were varied based on the two schedules in Table 5.2 and Table 5.3 respectively.

**Table 6.2- Schedule B (*R, S*) variations**

| Schedule B | |
|---|---|
| Month | Schedule |
| November guideline | November 1st to November 23rd |
| December guideline | November 24th to December 24th |
| January guideline | December 25th to January 24th |
| February guideline | January 25th to February 21st |

| | |
|---|---|
| March guideline | February 22nd to March 31st |

**Table 6.3 - Schedule C (*R*, *S*) variations**

| Schedule C | |
|---|---|
| Month | Schedule |
| November guideline | November 1st to November 23rd |
| December guideline | November 24th to December 24th |
| January guideline | December 25th to January 31st |
| February guideline | February 1st to February 28th |
| March guideline | March 1st to March 31st |

Based on Schedules B and C, the starting inventories on the first of the month were more likely to be the target (S) value for that month. This was achieved with the schedules by placing an order prior to the beginning of the month in the preceding month. The order was then fully received prior to the start of the month. This works in the case when the target level increases, but for those months where the target level decreases no order was placed to lower inventory levels to the target levels of that month.

## 6.2. Definition of the guideline variations

In this section we define the different variations of the guidelines that were analyzed using simulation. From Section 6.1 we identified several variations for the beginning inventory levels for November 1st and also have identified some variations of points in time counties should utilize particular months (*R*, *S*) values. Table 5.4 lists all possible variations that were tested through simulation and are identified as a guideline number.

Table 6.4 - Guideline variations

| Guideline Number | Definition |
|---|---|
| Actual | The beginning inventory is actual beginning inventory provided by ODOT and orders are actual orders provided by ODOT |
| 1 | The beginning inventory is actual beginning inventory provided by ODOT and implementing Schedule A |
| 2 | The beginning inventory level is the stock target level (S) for November and implementing Schedule A |
| 3 | The beginning inventory level is the stock target level (S) for December and implementing Schedule A |
| 4 | The beginning inventory level is the stock target level (S) for January and implementing Schedule A |
| 5 | The beginning inventory level is the stock target level (S) for March and implementing Schedule A |
| 6 | The beginning inventory level is the stock target level (S) for November and implementing Schedule B |
| 7 | The beginning inventory level is the stock target level (S) for December and implementing Schedule B |
| 8 | The beginning inventory level is the stock target level (S) for January and implementing Schedule B |
| 9 | The beginning inventory level is the stock target level (S) for March and implementing Schedule B |
| 10 | The beginning inventory level is the stock target level (S) for November and implementing Schedule C |
| 11 | The beginning inventory level is the stock target level (S) for December and implementing Schedule C |
| 12 | The beginning inventory level is the stock target level (S) for January and implementing Schedule C |
| 13 | The beginning inventory level is the stock target level (S) for March and implementing Schedule C |

## 6.3. Simulation results for Cuyahoga County

Simulations were run driven by data from November – March for every year 1998 through 2005, for each of the guidelines listed in

Table 6.4 for Cuyahoga County. Each guideline simulation was evaluated using 30 replications. In the 30 replications of each guideline, random variations are added to the supply process to induce some "worst case scenarios". These random "worst-case" supply scenarios result in longer than average resupply delivery times. When combined together with the historical usage scenarios, this worst-case supply methodology "stresses" the inventory management guidelines beyond what we expect to see in actual practice. For example, in these worst-case scenarios, the re-supply lead time to fill an order can extend several days beyond the 7-day guideline. Combined by an extended period of high usage, these worst-case scenarios show the limits of the suggested inventory guidelines. To find the best guideline used for all other counties, we looked at the average number of stockouts in the simulated scenarios for each year and accumulated them over the years for each guideline. The most important factor was to minimize instances of inventories falling to zero, which equates to a stockout. We also looked at average inventories, number of orders placed and received, order size, and also the average of the minimum season-long inventories. The number of orders received was the total number of truckload deliveries received at the county garage, while the number of orders placed was the total number of orders placed to the vendor.

To compare the guidelines we first ran the simulation with the actual used, received, and beginning inventories data supplied by ODOT for years from 1999 – 2005. The results of the runs over the 7 years are shown in Table 6.5.

**Table 6.5 - Simulation results with actual results for Cuyahoga 1999 – 2005**

| Year | Number of Stockouts | Ave. Inventory level | Ave. Amount Received | Ave. # of Order Received |
|---|---|---|---|---|
| 2005 | 0 | 12900 | 860 | 46 |
| 2004 | 0 | 21000 | 937 | 40 |
| 2003 | 0 | 15900 | 796 | 57 |
| 2002 | 0 | 21200 | 603 | 39 |
| 2001 | 0 | 12400 | 704 | 59 |
| 2000 | 0 | 13100 | 781 | 37 |
| 1999 | 0 | 14100 | 691 | 45 |

Utilizing the actual beginning inventories and the actual historical used salt amounts provided by ODOT, we then ran the simulation for guideline 1. This guideline used the given numbers and implements the ($R$, $S$)-inventory guideline. From Table 6.6 we see that just by implementing the ($R$, $S$)-inventory guideline with the actual beginning inventories we reduced the average inventories in all years and in some cases even decreased the number of orders received. This can be seen in Figure 6.2 where the inventory levels for the actual are graphed against guideline 1.

**Table 6.6 - Simulation results for guideline 1 for Cuyahoga 1999 – 2005**

| Year | Policy | Ave. # of Stockouts | ± CI | Ave. Inv. Level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amt. Received | ± CI | Ave. # of Order Rec. | ± CI | Ave. Min. Inv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 1 | 0 | 0 | 12500 | 123 | 12.7 | 0.31 | 850 | 34.7 | 49.5 | 2.32 | 11200 |
| 2004 | 1 | 0 | 0 | 15700 | 216 | 9.2 | 0.33 | 854 | 54.7 | 35.5 | 2.14 | 14400 |
| 2003 | 1 | 0 | 0 | 12400 | 115 | 13 | 0.32 | 823 | 35.3 | 48.1 | 2.31 | 11300 |
| 2002 | 1 | 0 | 0 | 12700 | 16.1 | 7.2 | 0.14 | 826 | 51.3 | 18.5 | 1.08 | 12500 |
| 2001 | 1 | 0 | 0 | 10500 | 148 | 12.4 | 0.3 | 839 | 36.9 | 46.2 | 2.11 | 9490 |
| 2000 | 1 | 0 | 0 | 11900 | 65.7 | 8.1 | 0.18 | 848 | 49.4 | 28.7 | 1.78 | 11500 |
| 1999 | 1 | 0.1 | 0.15 | 13300 | 162 | 8.3 | 0.17 | 861 | 55.1 | 33.3 | 2.15 | 12100 |

We also systematically explore the imapct of beginning-of-seasin inventories. We do this by running the different guidelines with different intitial stock target levels in November calculated from section 5.2 for Cuyahoga County. We first tested the stock target level for November as the beginning inventory level on November 1st by running guideline 2, 6, and 10. We found that beginning the year with November's target level gave the largest number of stockouts on average over the years. Table 5.7 shows the results of the simulations. Each year's result is averaged to get a 7 years average. The stockouts for each year are summed to get a total number of average stockouts for the 7 years.

**Table 6.7 - Simulation results for Cuyahoga for guidelines with November target level**

| Guideline | Total # of Ave. Stockouts | Ave. Inv. Level | Ave. # of Orders Placed | Ave. Amt. Received | Ave. # of Order Rec. | Ave. Min. Inv. |
|---|---|---|---|---|---|---|
| 2 | 4.10 | 7580 | 14.8 | 840 | 57.7 | 6050 |
| 6 | 2.43 | 7890 | 14.5 | 845 | 57.2 | 6340 |
| 10 | 2.43 | 8180 | 13.7 | 855 | 56.8 | 6650 |

The November ($R$, $S$) stock target level for Cuyahoga County is 3,540 tons, which is less than the 8,050 ton stock target level for the month of March. To mimic current practice, we considered using the higher March ($R$, $S$) target level for November. Utilizing the stock target level for March as the beginning inventory level for guidelines 5, 9, and 13 we found that stockouts on average were reduced. Table 6.8 shows the results of using the stock target level of March for the beginning inventory on November 1st.

**Table 6.8 - Simulation results for Cuyahoga for guidelines with March target level**

| Guideline | Total # of Ave. Stockouts | Ave. Inv. Level | Ave. # of Orders Placed | Ave. Amt. Received | Ave. # of Order Rec. | Ave. Min. Inv. |
|---|---|---|---|---|---|---|
| 5 | 1.73 | 8720 | 12.8 | 843 | 51.7 | 7610 |
| 9 | 0.967 | 8870 | 13.8 | 838 | 52.0 | 7590 |
| 13 | 0.967 | 9160 | 12.9 | 850 | 51.4 | 8460 |

Comparing Table 6.7 and Table 6.8 we found that as beginning inventories were increased total average stockouts decreased, but average and minimum average inventories increased. It is evident from the data in the tables that increasing beginning inventories reduced the number of orders placed and received by changing the average order amounts very little. Though average inventories were lower using the November stock target level it is more important to have no stockouts. These comparisons suggest that among this set of choices, the best alternative is to utilize March stock target level for the beginning inventory level. The best choice is guideline 9 or 13 because they have the lowest total average number of stockouts. The tie breaker would be the lowest orders placed and the average amount received. This would result in guideline 13, which is the guideline of utilizing the months of December and January's (*R*, *S*) guideline numbers seven days into the preceding month. We expect this guideline to be the best choice when we run the simulation with the December and January stock target levels.

Table 6.9 and Table 6.10 show the results of the simulation using the stock target level of 12,600 for December and 15,100 for January, respectively.

**Table 6.9 - Simulation results for Cuyahoga for guidelines with December target level**

| Guideline | Total # of Ave. Stockouts | Ave. Inv. Level | Ave. # of Orders Placed | Ave. Amt. Received | Ave. # of Order Rec. | Ave. Min. Inv. |
|---|---|---|---|---|---|---|
| 3 | 0.90 | 9840 | 12.3 | 836 | 46.7 | 8470 |
| 7 | 0.666 | 9730 | 12.9 | 836 | 46.7 | 8620 |
| 11 | 0.666 | 10000 | 12.1 | 844 | 46.5 | 8980 |

**Table 6.10 - Simulation results for Cuyahoga for guidelines with January target level**

| Guideline | Total # of Ave. Stockouts | Ave. Inv. Level | Ave. # of Orders Placed | Ave. Amt. Received | Ave. # of Order Rec. | Ave. Min. Inv. |
|---|---|---|---|---|---|---|
| 4 | 1.37 | 10700 | 11.9 | 832 | 44.0 | 9700 |
| 8 | 1.23 | 10500 | 12.5 | 830 | 44.1 | 9690 |
| 12 | 1.23 | 10800 | 11.6 | 840 | 43.6 | 9700 |

From Tables 5.9 and 5.10 we conclude that best choice is guideline 11, which uses December stock target level as the beginning inventory. This guideline minimizes the total number of average stockouts with lowest average orders placed and received. When examining the simulation results closer we found that in 1999 every guideline had an average stockout greater then or equal to .567 with guidelines 4, 8, and 12 having at least 1.1 stockouts. Based on a meeting with ODOT officials the results of the simulation are consistent with inventories in 1999. Many counties did see stockouts due to complications in receiving orders. We decided that the two best guidelines found from the simulation runs are guidelines 11 and 12. The comparisons between the two are shown in Table 6.11 and Table 6.12, including confidence intervals.

**Table 6.11 - Simulation results for guideline 11 for Cuyahoga 1999 – 2005**

| Year | Policy | Ave. # of Stockouts | ± CI | Ave. Inv. Level | ± CI | Ave. # of Orders Received | ± CI | Ave. Amt. Ordered | ± CI | Ave. # of Order Rec. | ± CI | Ave. Min. Inv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 11 | 0 | 0 | 9830 | 176 | 15.4 | 0.25 | 844 | 34.5 | 59.1 | 2.72 | 9830 |
| 2004 | 11 | 0.1 | 0.2 | 9900 | 193 | 14.1 | 0.27 | 827 | 34.4 | 57 | 2.63 | 8610 |
| 2003 | 11 | 0 | 0 | 9430 | 133 | 15.5 | 0.24 | 838 | 35.7 | 59.7 | 2.83 | 8180 |
| 2002 | 11 | 0 | 0 | 10600 | 19.3 | 8.17 | 0.14 | 825 | 43.3 | 23.9 | 1.37 | 10400 |
| 2001 | 11 | 0.033 | 0.07 | 10000 | 211 | 12.3 | 0.26 | 841 | 40.4 | 50.4 | 2.93 | 7790 |
| 2000 | 11 | 0 | 0 | 10100 | 96 | 9.2 | 0.16 | 852 | 48.1 | 34.9 | 2.19 | 9310 |
| 1999 | 11 | 0.533 | 0.7 | 10200 | 182 | 9.8 | 0.28 | 883 | 54.6 | 40.7 | 2.66 | 8750 |

**Table 6.12 - Simulation results for guideline 12 for Cuyahoga 1999 – 2005**

| Year | Policy | Ave. # of Stockouts | ± CI | Ave. Inv. Level | ± CI | Ave. # of Orders Received | ± CI | Ave. Amt. Ordered | ± CI | Ave. # of Order Rec. | ± CI | Ave. Min. Inv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 12 | 0 | 0 | 10700 | 133 | 14.7 | 0.33 | 837 | 32.7 | 56.4 | 2.29 | 9600 |
| 2004 | 12 | 0.133 | 0.27 | 10400 | 190 | 13.5 | 0.27 | 831 | 37.2 | 53.5 | 2.47 | 9210 |
| 2003 | 12 | 0 | 0 | 10100 | 96.6 | 15.7 | 0.19 | 833 | 31.9 | 56.8 | 2.31 | 9360 |
| 2002 | 12 | 0 | 0 | 11400 | 17.8 | 7.67 | 0.18 | 821 | 48.2 | 20.7 | 1.17 | 11200 |
| 2001 | 12 | 0 | 0 | 10400 | 205 | 12.4 | 0.3 | 831 | 37.8 | 47.7 | 2.59 | 8490 |
| 2000 | 12 | 0 | 0 | 11100 | 91.8 | 8.3 | 0.17 | 860 | 50.5 | 31.5 | 1.98 | 10500 |
| 1999 | 12 | 1.1 | 0.77 | 11200 | 205 | 9.1 | 0.21 | 864 | 55.7 | 38.7 | 2.52 | 9570 |

From the simulation we found that the higher stockout number for guideline 12 was caused by a large average stockout in 1999. Outside of the results of 1999 for all guidelines we found that the average number of stockouts for guideline 11 and 12 is the lowest and equal for the two guidelines. The tie breaker would thus go to guideline 12 because of lower average orders placed and received. This guideline also maximized the average minimum inventory, which is important because of the unpredictable nature of the weather and supply. Results of the simulations for Cuyahoga County for all the years and guidelines can be found in Appendix 2.

Figure 6.2 graphs the result of guideline 1 for 2005 found in Table 5.6 with the results of the actual inventory level for 2005 found in Table 5.5. Guideline 1 merely implements the ($R$, $S$)-inventory guideline and uses the actual beginning inventories provided by ODOT as the inventory level on November 1$^{st}$. The results in Figure 6.2 and Figure 6.3 were computed by taking the simulation results over the 30 replications and averaging them out for each day.

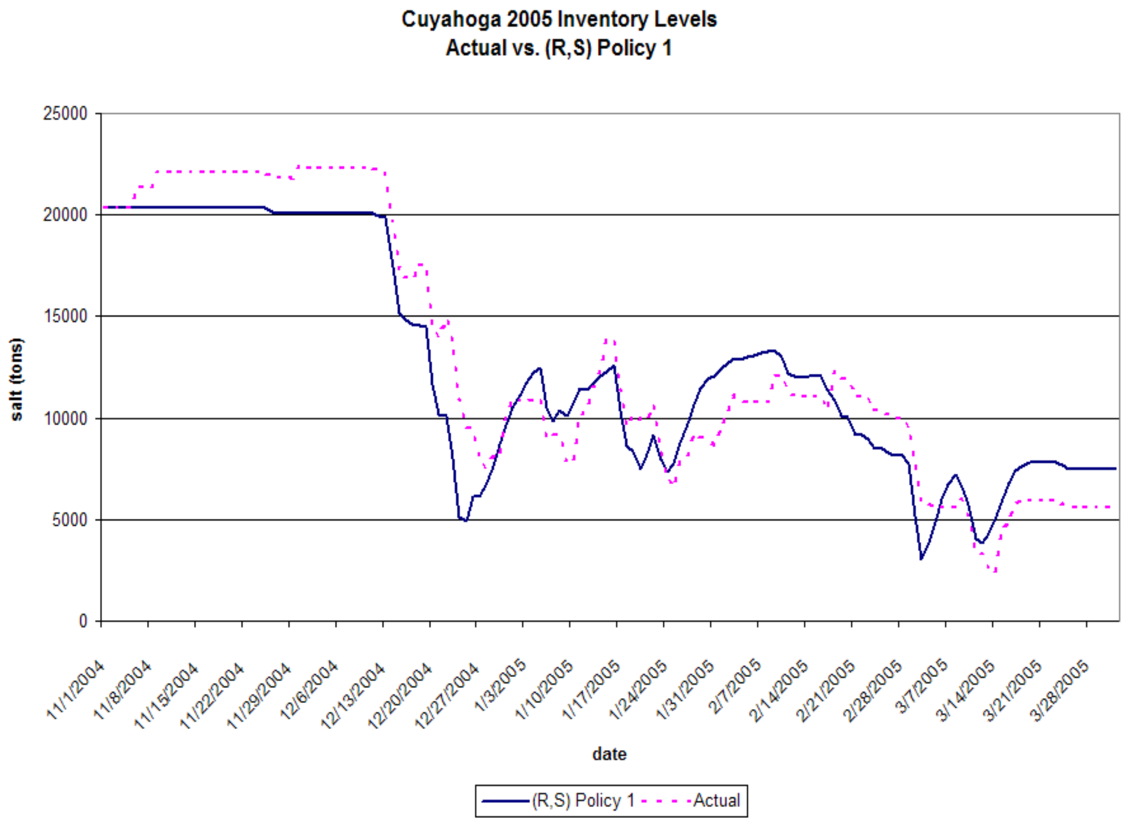



**Figure 6.2 - Cuyahoga actual inventories vs. inventories applying (R, S) guideline 1 for November 2004 – March 2005**

Figure 6.3 shows the inventory level for November 2004 – March 2005 for Cuyahoga utilizing the best overall guideline for all counties, guideline 12. Guideline 12 starts the season on November 1st with the stock target level for January and the (R, S) guideline for December and January will begin 7 days into the preceding months with no changes to the (R, S) parameters in February and March. Figure 6.4 and Figure 6.5 compare the received amount streams associated with actual received amounts provided by ODOT and then the received amount streams found through simulation with the implementation of the proposed (R, S)-inventory guideline. The results in Figure 6.5 show one replication of received amounts and graphing them for the time period between November 1st and March 31st.

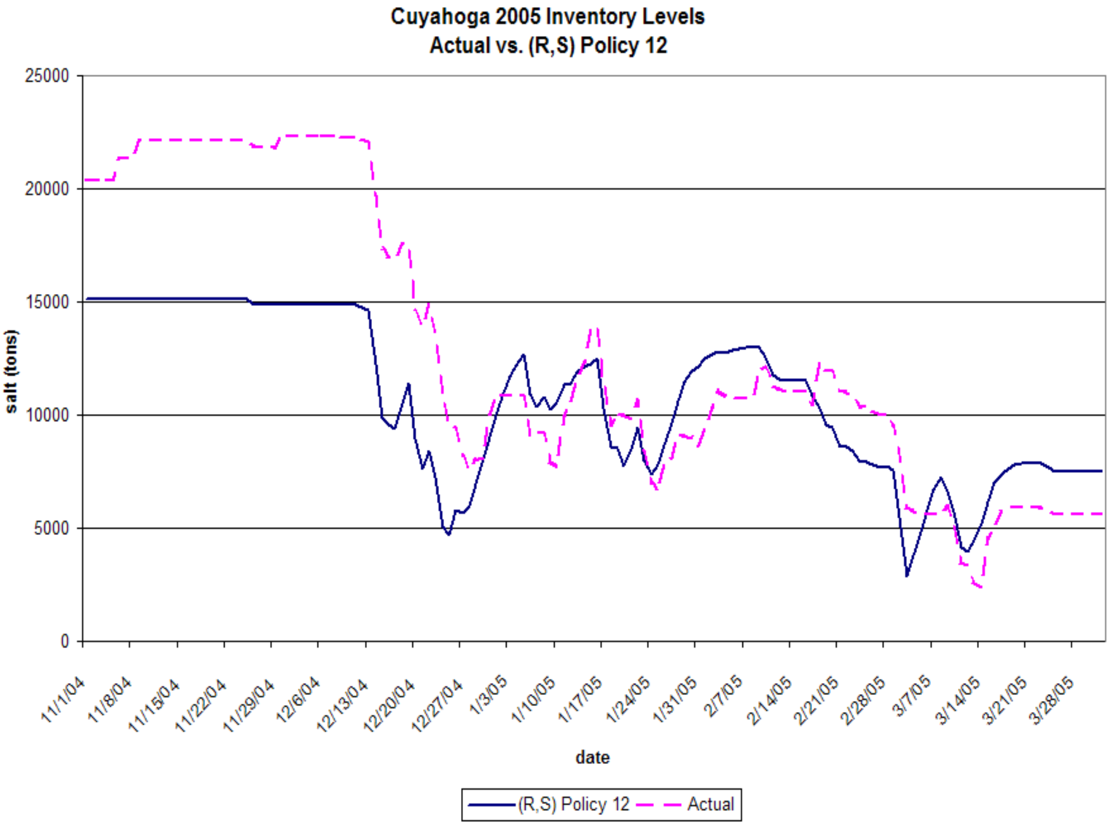



**Figure 6.3 - Cuyahoga actual inventories vs. inventories applying (R, S) guideline 12 for November 2004 – March 2005**

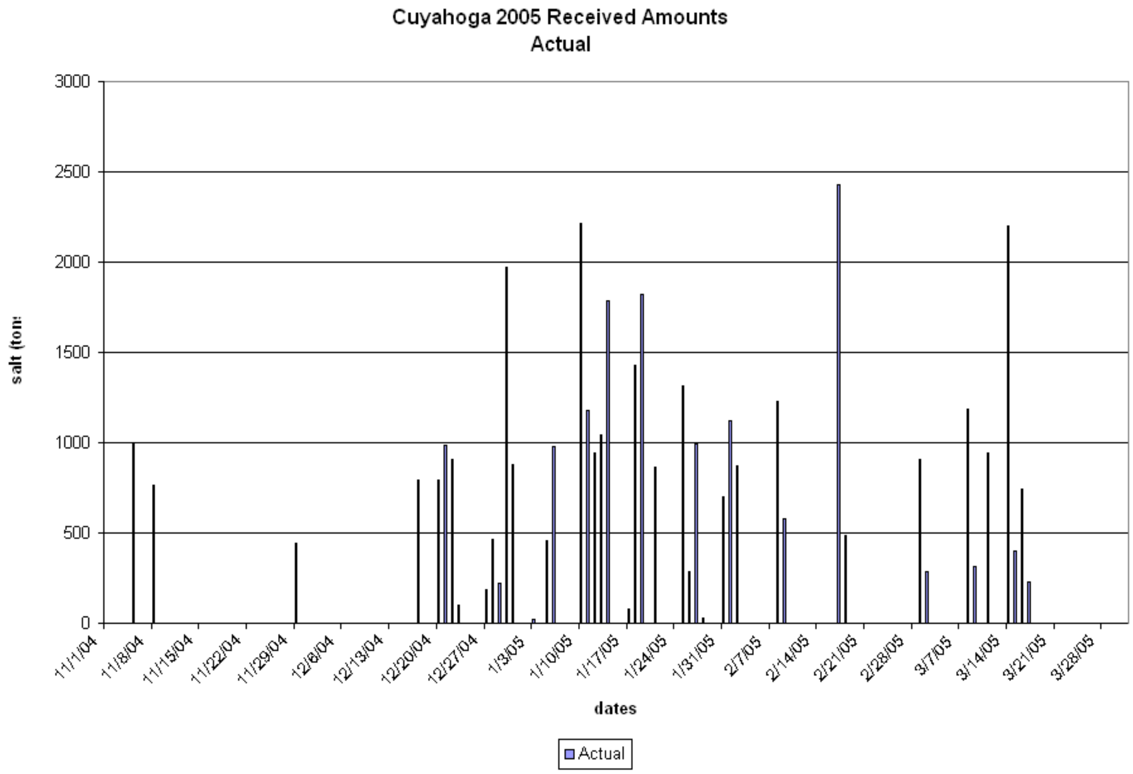



**Figure 6.4 - Cuyahoga actual received amounts from November 2004 – March 2005**

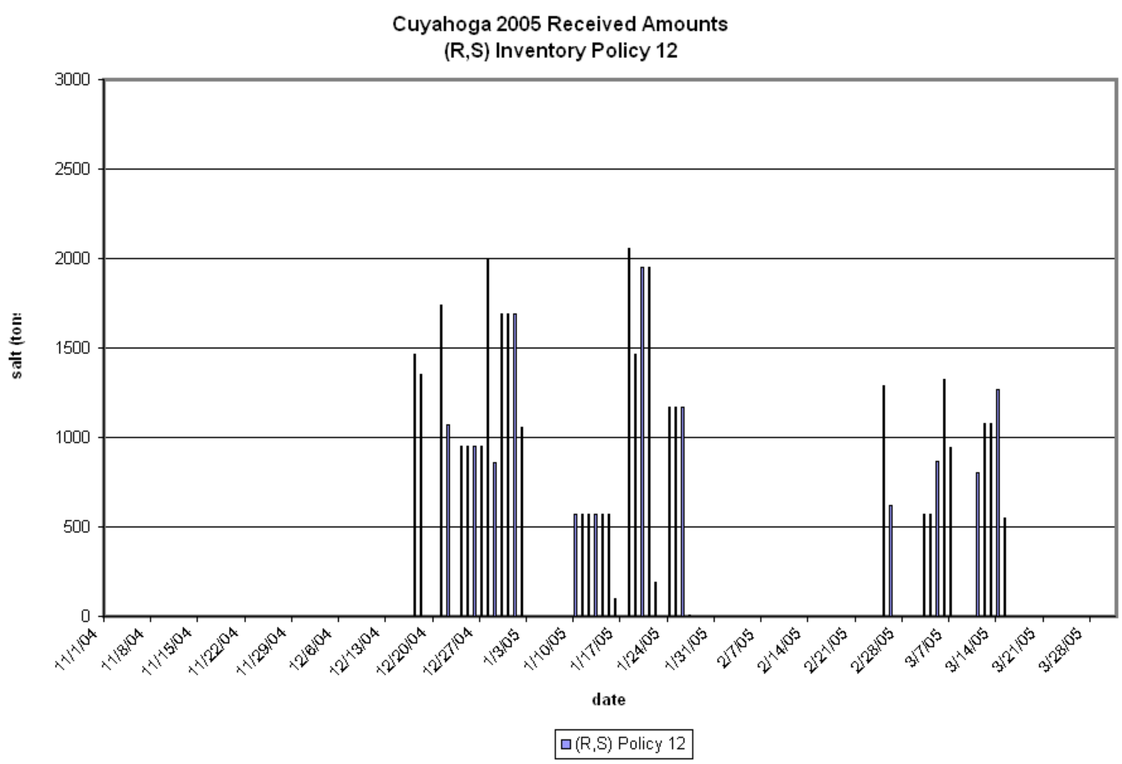



**Figure 6.5 - Cuyahoga (R, S) guideline received amounts from November 2004 – March 2005**

## 6.4. Simulation results for Lucas County

The use of Cuyahoga County results was twofold. First, the results were used to study the performance of the guideline in a simulated environment. Second the simulation was used to determine the best guideline for the implementation of the (*R*, *S*)-inventory guideline. The reason for using Cuyahoga County for testing was due to its high salt usage. Because the simulation and guideline parameters were calculated cumulatively for the county, it is important to test the parameters of a county that only has one garage. Lucas County only has one garage. Unfortunately the (*R*, *S*) numbers for Lucas are not based on the weather regression, but rather directly from historical data. From the Roelants and Muyldermans (2002) paper it was found that using the weather regression model to calculate the (*R*, *S*) parameters is more accurate than the historical data, but historical data parameters still will perform well. If the model using historical data performs well in the simulation then we expect that the weather regression based model will perform equally well or better.

The simulation model was run using guideline 12, which was found to perform best when using the (*R*, *S*)-inventory guideline. Table 5.13 shows the results for the simulation running the actual guideline, where historical usage, received, and beginning numbers were used. Tables 5.14 and 5.15 show the simulation results with 30 replications for Guideline 1 and 12 respectively. Guideline 12 is the guideline that was chosen through the analysis of Cuyahoga County and this guideline utilizes the stock target level of January as the beginning inventory level for November 1$^{st}$ and beginning guidelines for December and January 7 days into the prior month.

**Table 6.13 - Simulation results with actual numbers for Lucas 1999 – 2005**

| Year | Number of Stockouts | Ave. Inventory level | Ave. Amount Received | Ave. # of Order Received |
|---|---|---|---|---|
| 2005 | 0 | 1540 | 583 | 7 |
| 2004 | 0 | 1580 | 433 | 8 |
| 2003 | 0 | 1330 | 767 | 7 |
| 2002 | 0 | 1470 | 331 | 3 |
| 2001 | 0 | 1350 | 607 | 10 |
| 2000 | 0 | 2560 | 502 | 10 |
| 1999 | 0 | 1100 | 635 | 7 |

**Table 6.14 - Simulation results for guideline 1 for Lucas 1999 – 2005**

| Year | Policy | Ave. # of Stockouts | ± CI | Ave. Inv. Level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amt. Received | ± CI | Ave. # of Order Rec. | ± CI | Ave. Min. Inv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 1 | 0 | 0 | 1400 | 2.43 | 14 | 0 | 258 | 7.45 | 15 | 0.49 | 1390 |
| 2004 | 1 | 0 | 0 | 1350 | 4.37 | 8.13 | 0.13 | 317 | 14.7 | 9.23 | 0.57 | 1340 |
| 2003 | 1 | 0 | 0 | 1060 | 4.19 | 17.9 | 0.11 | 275 | 8.92 | 20.4 | 0.76 | 1010 |
| 2002 | 1 | 0 | 0 | 1460 | 0.38 | 5 | 0 | 247 | 10.7 | 5.33 | 0.37 | 1450 |
| 2001 | 1 | 0 | 0 | 1210 | 2.38 | 17.9 | 0.09 | 293 | 9.12 | 20.5 | 0.66 | 1180 |
| 2000 | 1 | 0 | 0 | 1270 | 1.84 | 2 | 0 | 487 | 57.6 | 3.37 | 0.61 | 1240 |
| 1999 | 1 | 0 | 0 | 1280 | 1.52 | 14 | 0 | 304 | 10.9 | 16.2 | 0.63 | 1260 |

**Table 6.15 - Simulation results for guideline 12 for Lucas 1999 – 2005**

| Year | Policy | Ave. # of Stockouts | ± CI | Ave. Inv. Level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amt. Received | ± CI | Ave. # of Order Rec. | ± CI | Ave. Min. Inv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 12 | 0 | 0 | 1320 | 2.75 | 14.9 | 0.11 | 258 | 6.6 | 16 | 0.44 | 1300 |
| 2004 | 12 | 0 | 0 | 1450 | 0.7 | 9 | 0 | 300 | 10.9 | 9.77 | 0.42 | 1440 |
| 2003 | 12 | 0 | 0 | 1280 | 0.6 | 16.9 | 0.11 | 251 | 6.46 | 18.1 | 0.55 | 1270 |
| 2002 | 12 | 0 | 0 | 1450 | 0.36 | 5 | 0 | 228 | 9.2 | 5.3 | 0.31 | 1440 |
| 2001 | 12 | 0 | 0 | 1300 | 2.13 | 16 | 0.07 | 299 | 10.5 | 18.4 | 0.71 | 1290 |
| 2000 | 12 | 0 | 0 | 1530 | 0.12 | 1 | 0 | 303 | 17.6 | 1.1 | 0.15 | 1530 |
| 1999 | 12 | 0 | 0 | 1400 | 3.82 | 13 | 0.07 | 299 | 11.3 | 14.8 | 0.67 | 1370 |

Figure 6.6 graphs the actual inventory found through simulation with the inventory level found through the simulation of guideline 1, which only implements the ($R$, $S$) guideline with actual beginning inventory. Figure 6.7 graphs the actual inventories with the inventory levels of guideline 12. Both Figure 6.6 and Figure 6.7 are graphed with the results of the 30 replications. Figure 6.8 shows the actual received amounts for the 2005 winter year and Figure 6.9 shows the order stream for the same time period using the ($R$, $S$)-inventory guideline.

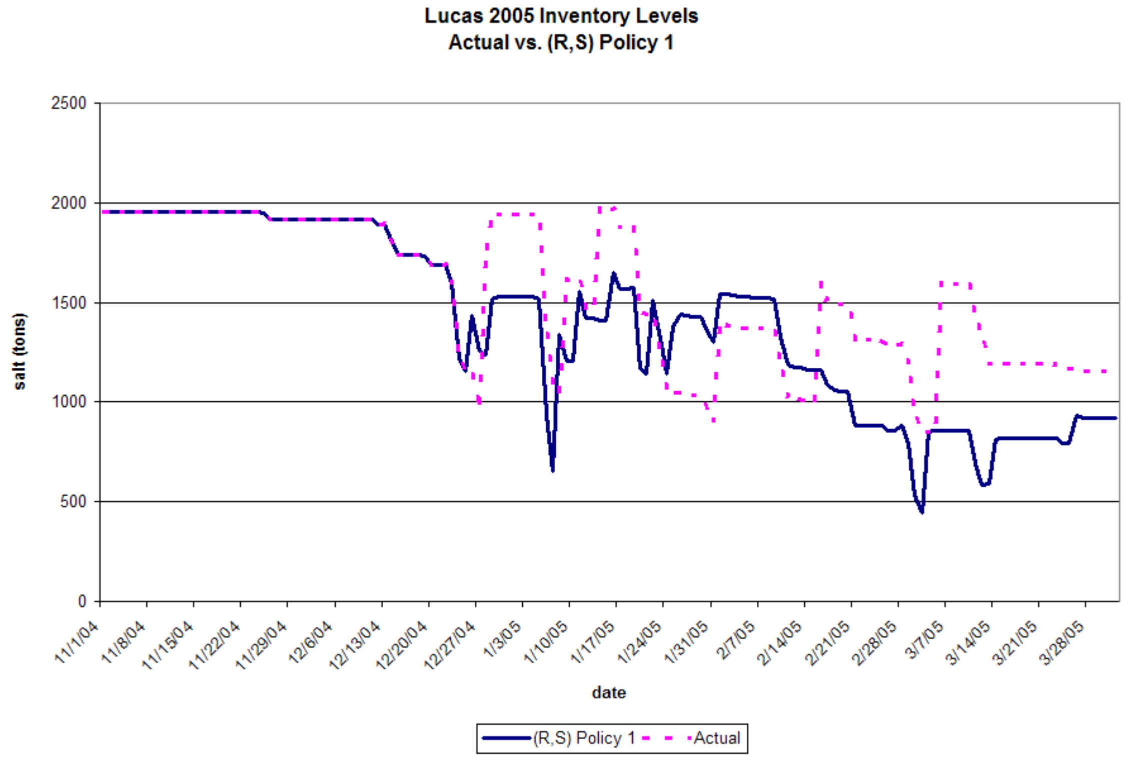



**Figure 6.6 - Lucas actual inventories vs. inventories applying (R, S) guideline 1 for November 2004 – March 2005**

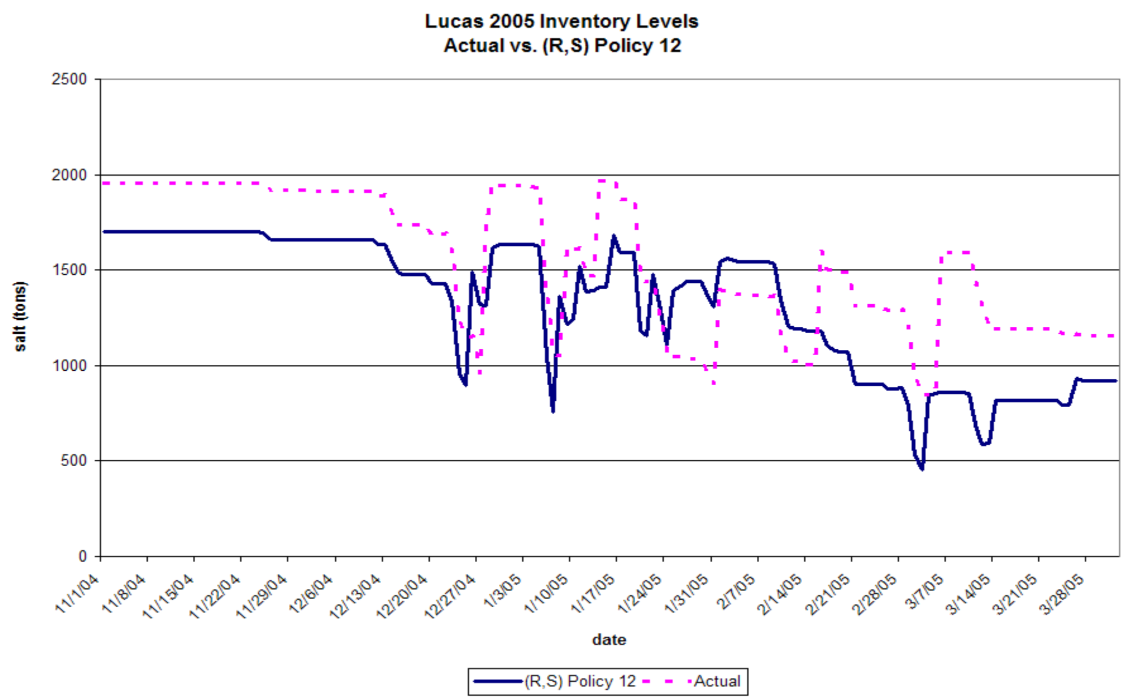



**Figure 6.7 - Lucas actual inventories vs. inventories applying (R, S) guideline 12 for November 2004 – March 2005**

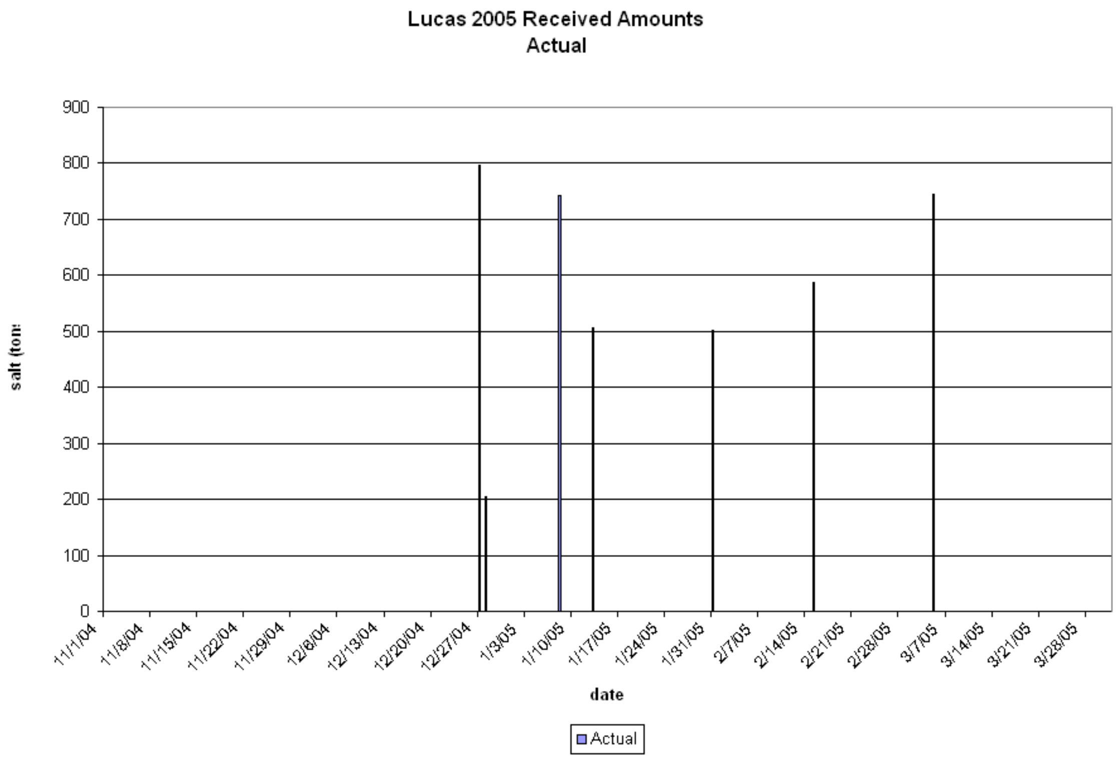



**Figure 6.8 - Lucas actual received amounts from November 2004 – March 2005**

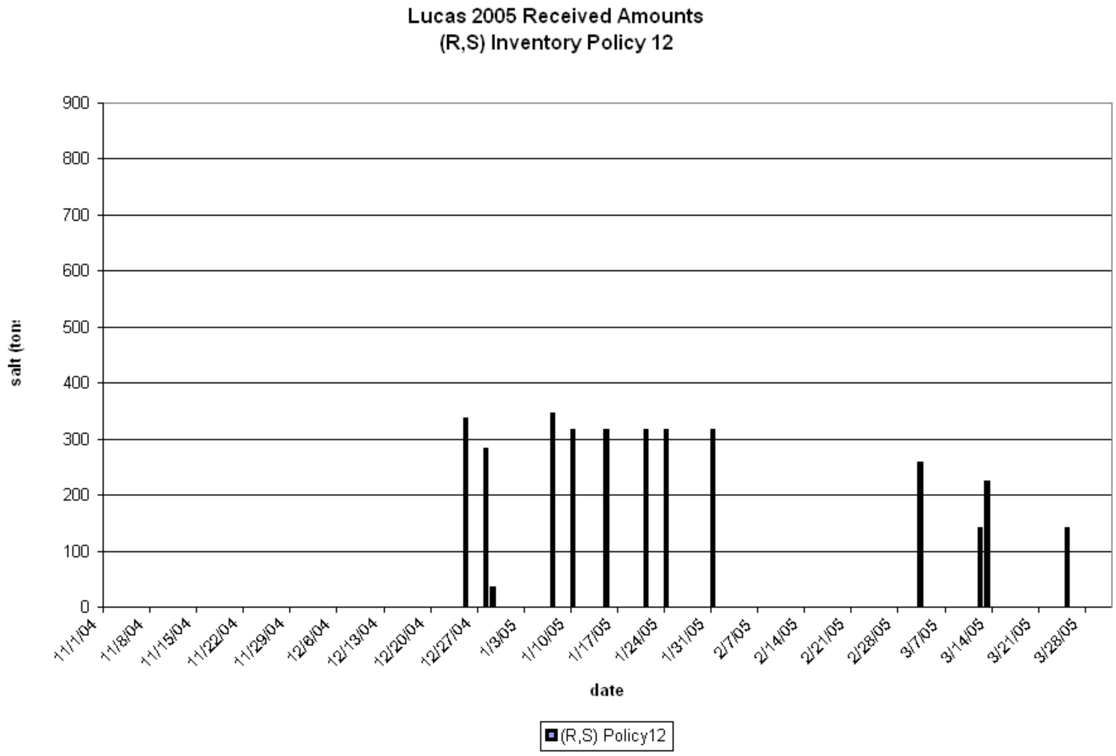



**Figure 6.9 - Lucas (R, S) guideline 12 received amounts November 2004 – March 2005**

Based on the simulation findings we find that even though the historical data method is not as accurate, it may still be used effectively in counties where weather data is not available. The test for a weather regression model for the use by more then one county still requires the collection of the weather data from that county. For a county without the means to apply a weather regression model to their weather data, the result of this simulation is that (*R*, *S*) guidelines based on historical data can perform well. From the simulation results for Lucas County, we can see that an (*R*, *S*) guideline developed specifically from a set of data for either an entire county or one garage will be an effective inventory guideline. This is based on the analysis of models developed for a county using data from multiple garages such as Cuyahoga and an (*R*, *S*)-inventory guideline developed for an entire county with only one garage.

## 6.5. Simulation results for Summit County and test for universal model

Simulation was used to determine whether models developed for one county can be used on other counties in similar areas. It was found that Summit and Cuyahoga could be located in similar weather zones and that using Cuyahoga County's weather regression model can be used to calculate the predictions for Summit County. The predictions found by this method are used to calculate an additional (*R*, *S*)-inventory guideline for Summit County. This is in addition to the original (*R*, *S*)-inventory guideline from Summit's weather regression model. The different methods to calculate the predictions and thus the inventory guideline are summarized in Table 5.16. Table 5.17 lists the mean squared error of the predictions calculated through the different weather regression models. Table 5.17 results suggest that the best method to calculate the predictions from the weather regression model and the (*R*, *S*)-inventory guideline is scenario 2. Scenario 2 calculated the (*R*, *S*)-inventory guideline for Summit County using the model developed for Cuyahoga with weather data from Summit County.

**Table 6.16 - Regression methods tested**

| County | Scenario # | Scenarios |
|---|---|---|
| Summit | 1 | Summit weather model with Summit weather data |
| | 2 | Cuyahoga weather model with Summit weather data taking into account percent difference in lane miles |
| | 3 | Mahoning weather model with Summit weather data taking into account percent difference in lane miles |
| Cuyahoga | 4 | Cuyahoga weather model with Cuyahoga weather data |
| | 5 | Summity weather model with Cuyahoga weather data taking into account percent difference in lane miles |
| | 6 | Mahoning weather model with Cuyahoga weather data taking into account percent difference in lane miles |
| Mahoning | 7 | Mahoning weather model with Mahoning weather data |
| | 8 | Summit weather model with Mahoning weather data taking into account percent difference in lane miles |
| | 9 | Cuyahoga weather model with Mahoning weather data taking into account percent difference in lane miles |

**Table 6.17 - Mean squared error for regression scenarios**

| | Mean Square Errors | | | | |
|---|---|---|---|---|---|
| Scenario | November | December | January | February | March |
| 1 | 91.6 | 118000 | 174000 | 109000 | 50200 |
| 2 | 54000 | 238000 | 513000 | 175000 | 153000 |
| 3 | 517000 | 408000 | 1110000 | 302000 | 178000 |
| 4 | 10200 | 461000 | n/a | n/a | n/a |
| 5 | 285000 | 1270000 | n/a | n/a | n/a |
| 6 | 511000 | 3090000 | n/a | n/a | n/a |
| 7 | 3420 | 288000 | 449000 | 208000 | 107000 |
| 8 | 82600 | 455000 | 1040000 | 561000 | 202000 |
| 9 | 46400 | 396000 | 1410000 | 724000 | 318000 |

By using the weather regression model developed for Cuyahoga on Summit (scenario 2), taking into account lane mileage, predictions were made for Summit. These predictions were then used to calculate the safety stock, mean usage during the lead time, reorder points, and target levels. First, the model is run using the (*R*, *S*) parameters developed through the model developed for Summit County. Second, this model is compared with the output from the parameters as calculated from the Cuyahoga model on Summit. It is assumed that the best model when run through the simulation is the one using the county that it was originally developed for, but that is not the purpose of this simulation. The purpose is to determine whether it is appropriate for one county to use models developed for another county if they are in similar weather areas. From the analysis of all the counties, it was determined that Summit is the only county most accurately predicted from another county's weather regression that was calculated. Given that the model performs well, a smaller county could utilize a larger counties weather model by collecting their relevant weather data and then adjust for the lane mileage differences. These predictions can then be used to calculate their own reorder points and target levels.

The model performs well in the case of using the Summit model specifically for Summit. The question is whether the weather regression model can be used from one county and can be used on another. This question was answered by running the simulation with the parameters calculated by using the weather regression model from Cuyahoga County on Summit. In Tables 5.18 – 5.20 we compare the results for the actual numbers with that of the different weather models for Summit County.

**Table 6.18 - Simulation results with actual numbers for Summit 1999 – 2005**

| Year | Number of Stockouts | Ave. Inventory level | Ave. Amount Received | Ave. # of Orders Received |
|---|---|---|---|---|
| 2005 | 0 | 8580 | 590 | 37 |
| 2004 | 0 | 6790 | 838 | 17 |
| 2003 | 0 | 7330 | 545 | 34 |
| 2002 | 0 | 10700 | 905 | 10 |
| 2001 | 0 | 7300 | 754 | 24 |
| 2000 | 0 | 7610 | 545 | 26 |
| 1999 | 0 | 8360 | 752 | 20 |

**Table 6.19 - Simulation results for Summit County by utilizing (R, S) parameters found through Summit weather model 1999 – 2005**

| Year | Policy | Ave. # of Stockouts | ± CI | Ave. Inv. Level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amt. Received | ± CI | Ave. # of Order Rec. | ± CI | Ave. Min. Inv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 12 | 0 | 0 | 4670 | 40.6 | 13.8 | 0.25 | 563 | 33.2 | 32.2 | 2.35 | 4360 |
| 2004 | 12 | 0 | 0 | 4420 | 41.9 | 14.4 | 0.32 | 573 | 33.5 | 34.8 | 2.2 | 4230 |
| 2003 | 12 | 0 | 0 | 4330 | 32.5 | 16.9 | 0.09 | 574 | 32.1 | 39.5 | 2.55 | 4080 |
| 2002 | 12 | 0 | 0 | 4800 | 8.38 | 8.97 | 0.07 | 569 | 38.3 | 17 | 1.42 | 4760 |
| 2001 | 12 | 0 | 0 | 4360 | 44.7 | 15.5 | 0.21 | 579 | 33.2 | 35.3 | 2.3 | 4030 |
| 2000 | 12 | 0 | 0 | 4700 | 31.3 | 8.93 | 0.14 | 587 | 39.7 | 21 | 1.82 | 4390 |
| 1999 | 12 | 0.033 | 0.07 | 4700 | 48.5 | 11.8 | 0.33 | 582 | 35.5 | 29 | 2.25 | 4340 |

**Table 6.20 - Simulation results for Summit County by utilizing (R, S) parameters found through Cuyahoga weather model 1999 – 2005**

| Year | Policy | Ave. # of Stockouts | ± CI | Ave. Inv. Level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amt. Received | ± CI | Ave. # of Order Rec. | ± CI | Ave. Min. Inv. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2005 | 12 | 0 | 0 | 4180 | 24.7 | 16.9 | 0.13 | 560 | 32.9 | 32.4 | 2.18 | 4010 |
| 2004 | 12 | 0 | 0 | 4140 | 40.1 | 16.7 | 0.28 | 546 | 27 | 35.9 | 2.05 | 3980 |
| 2003 | 12 | 0 | 0 | 3850 | 20.6 | 20 | 0.24 | 551 | 27.1 | 40.1 | 2.24 | 3730 |
| 2002 | 12 | 0 | 0 | 4310 | 4.56 | 10 | 0 | 538 | 41.3 | 17.9 | 1.44 | 4270 |
| 2001 | 12 | 0 | 0 | 4070 | 42.1 | 17.4 | 0.27 | 551 | 30.5 | 36.6 | 2.31 | 3850 |
| 2000 | 12 | 0 | 0 | 4150 | 18 | 10.6 | 0.19 | 565 | 40.3 | 21.4 | 1.7 | 3960 |
| 1999 | 12 | 0.233 | 0.48 | 4360 | 46.7 | 13.7 | 0.26 | 563 | 35.8 | 30.3 | 2.31 | 3920 |

From the simulation results we find that both guidelines drastically reduce the average inventory levels and even in some years reduce the number of orders received at the garages. We find that both guidelines resulted in stockouts in 1999, but the number of stockout average .233. We expected the simulation results using the Summit weather model on Summit to perform better. The guideline does reduce the average number of stockouts, but increases the average inventory level. Overall it seems as though a model developed for one county can be used to calculate the (*R*, *S*)-inventory guideline for another smaller county by taking into account lane mileage differences and relevant weather variables. Figure 6.10 graphs the inventory levels of both (*R*, *S*)-inventory guidelines for Summit County with the actual inventory levels. For these results the simulation was run with 30 replications. Figure 6.11 – Figure 6.13 graph the received amounts comparing the actual received amounts with each (*R*, *S*)-inventory guideline developed for Summit County.

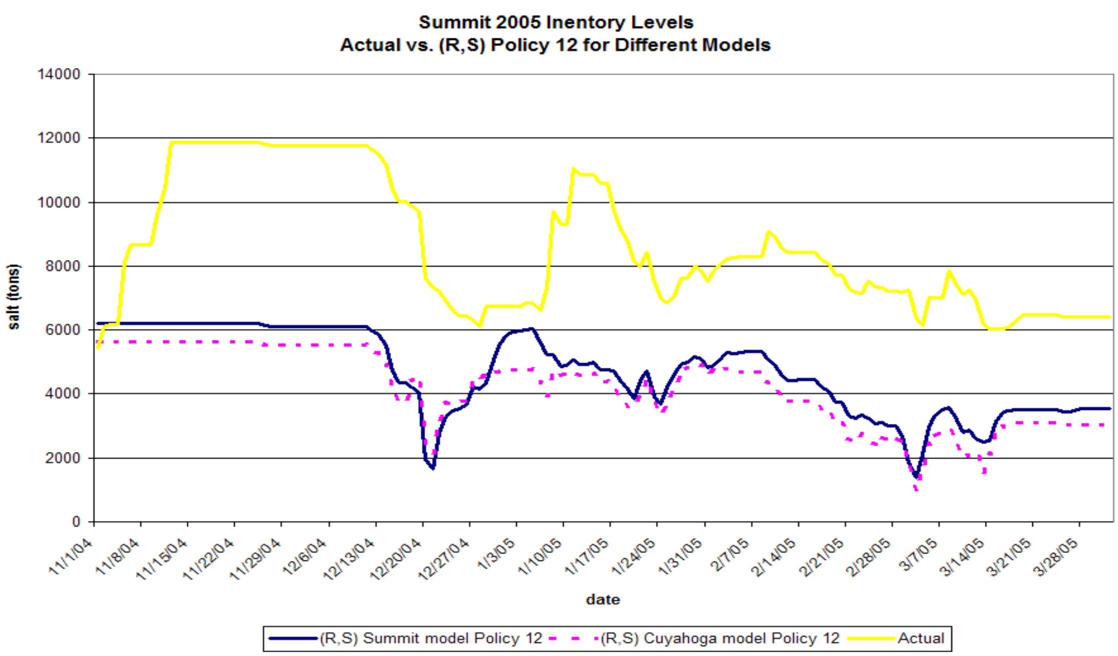



**Figure 6.10 - Summit County inventory levels comparing actual vs. different models for guideline 12 November 2004 – March 2005**

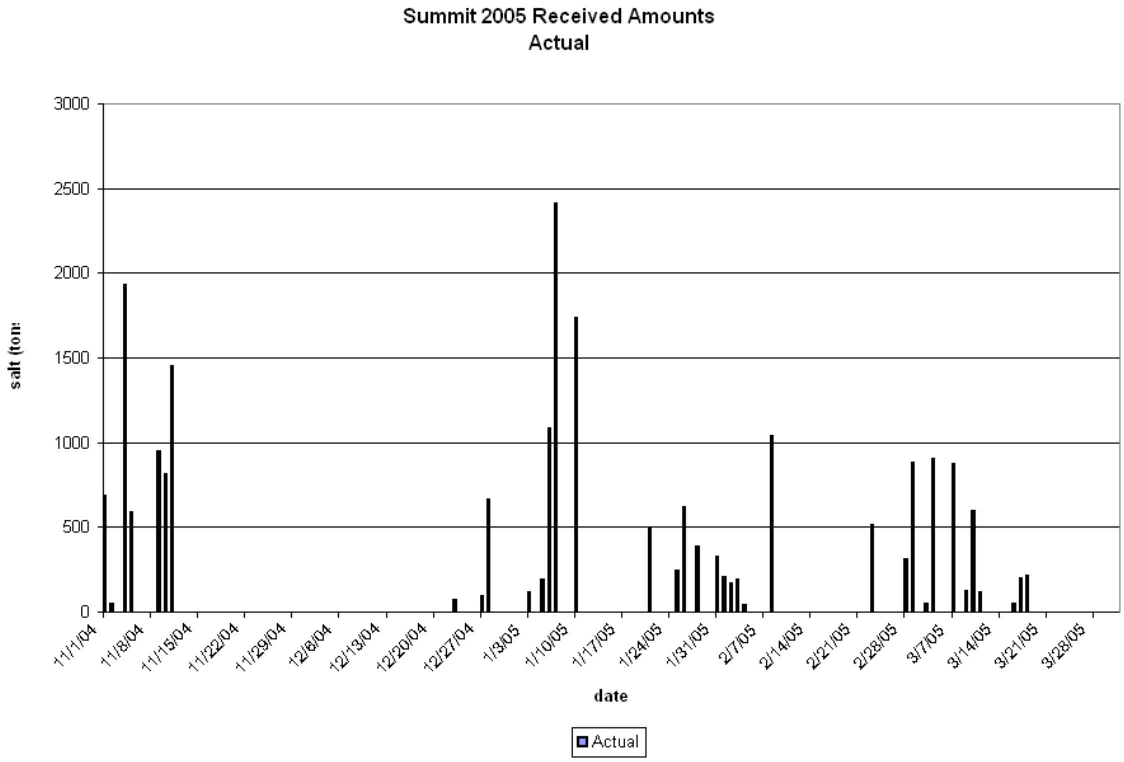



**Figure 6.11 - Summit actual received amounts from November 2004 – March 2005**

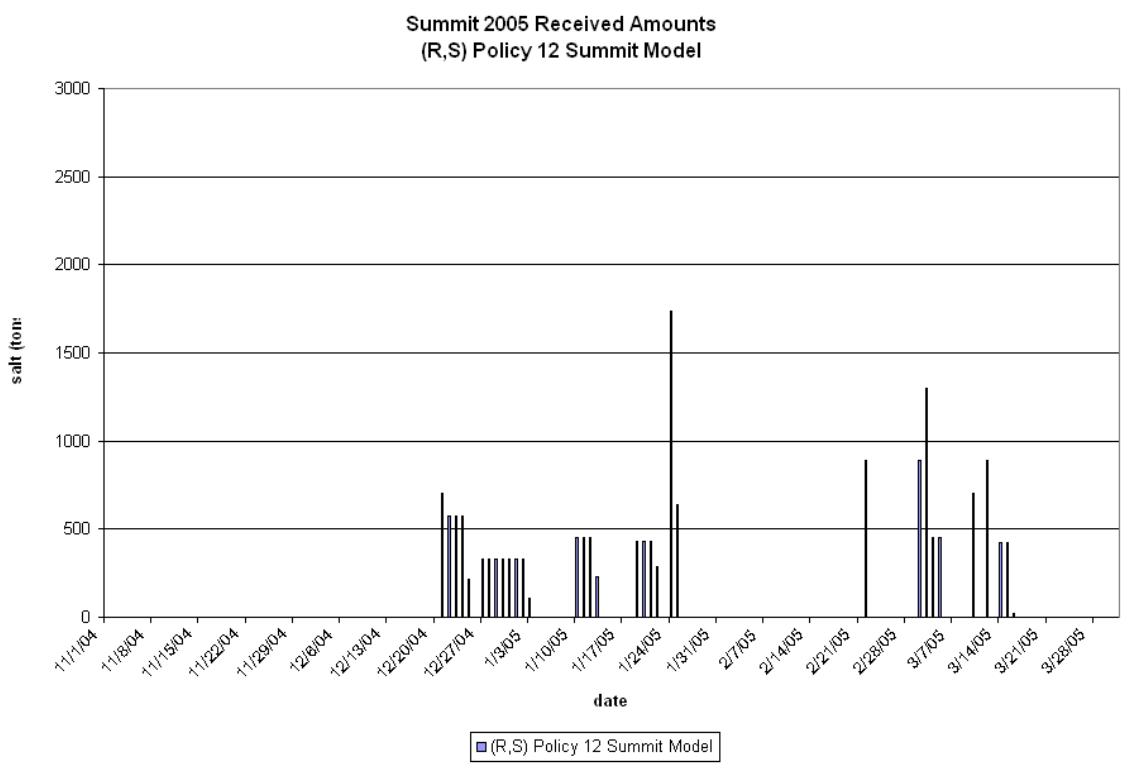



**Figure 6.12 - Summit received amounts November 2004 – March 2005 using Summit model**

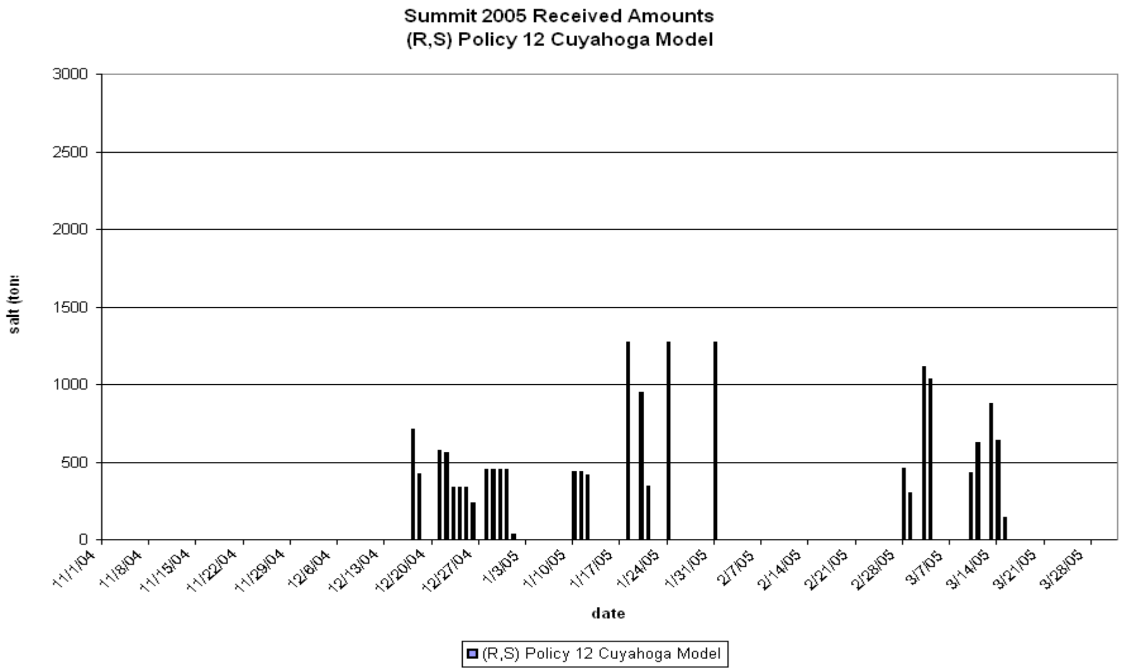



**Figure 6.13 - Summit received amounts November 2004 – March 2005 using Cuyahoga model**

In most cases using the Cuyahoga model for Summit produced similar number of received orders. The results of these different ($R$, $S$)-inventory guidelines for Summit County, are that indeed surrounding counties can use the weather regression model of a county in a similar weather zone as depicted by Figure 4.11. This is important as now regression models for only the 8 larger cities and their counties need to be calculated. These 8 regression models can be used to support the computation of ($R$, $S$) inventory guideline parameters for all 88 counties in Ohio, providing each county has relevant weather data. Finally, it is best for a county to use the model that was developed for that county. Using a model from another county should be reserved only for smaller surrounding counties in similar weather zones.

# 7. Analysis of County and Vendor Storage Capacity

In this chapter we review the county and vendor storage capacity. We define storage capacity to be the maximum amount of salt that can be stored on site at any time. For the county analysis, we identify counties where there may be insufficient storage to support a normal pattern of orders or the required level of service. For the vendors, we identify how vendor stockpile storage capacity has varied in comparison to the volumes actually shipped to ODOT county locations.

## 7.1. County Storage Capacity Analysis

In this section we examine the maximum target stock levels for each county (obtained on the basis of the ($R$, $S$) inventory guideline parameters) and the county salt storage capacity. This storage capacity is based on data from September 2006. This analysis is intended to identify those counties which have insufficient or marginally sufficient storage capacity to support adequate inventories to maintain acceptable levels of service for salt usage.

The terminology used in the county storage capacity analysis is as follows:

- **Maximum Target Stock Level:** Target stock level is the maximum amount of salt that is needed to be stored at a county (according to the ($R$, $S$) inventory guideline). The target stock level is based on the historical usage of salt in a county, and has a different value for every month. The maximum target stock level is defined as the maximum of all target stock level across all the months. (January is typically the highest usage month for each county.)
- **County Storage Capacity:** The maximum amount of salt a county can hold, i.e. the sum of the capacities of all salt storage bins in a county.
- **Difference:** The difference between the county storage capacity and maximum target stock level, i.e. (County Storage Capacity – Maximum Target Stock Level)
- **Percentage:** The difference divided by county storage capacity multiplied by 100, i.e. $\left( {}^{Difference}\!\big/_{County\,Storage\,Capacity} \right) * 100\%$.

Table 7.3 (page 84) shows an overall listing of these four measures for all counties. In this table, counties are marked that have a storage capacity that exceeds the maximum target stock by 20% or less.. These counties that have a deficit in storage capacity are listed separately in Table 7.1.

We can observe from Table 7.1 that Richland and Erie County's salt storage capacity is below the necessary storage, with a 51% and 16% shortage of storage capacity, respectively. Because of this shortage of storage capacity, there will be more frequent orders from these locations, as well as the higher likelihood of shortages. These counties must be considered for storage expansion beyond the levels shown in the table based on this analysis.

We also observe in Table 7.1 that Lucas, Crawford and Ross Counties have a storage capacity that is only marginally higher than the maximum target stock level. If usage in these counties grows, then the storage capacities may be insufficient to support a normal ordering pattern and acceptable levels of service. Consideration of expansion of storage capacity in the near future for these counties beyond the levels shown in the table is warranted.

**Table 7.1 - Counties that have critical or marginal storage capacity measured as a percentage**

| County | Maximum Target Stock Level (Tons) | County Storage Capacity (Tons) | Diference | Percentage(%) |
|---|---|---|---|---|
| Lucas | 1700 | 2000 | 300 | 15 |
| Crawford | 2550 | 2800 | 250 | 9 |
| Erie | 2560 | 2200 | -360 | -16 |
| Richland | 3470 | 2300 | -1170 | -51 |
| Ross | 2680 | 2900 | 220 | 8 |

The summary of all counties in Table 7.3 shows two counties that have storage capacity that have less than 550 tons of excess storage compared to the maximum target stock level. Although these counties did not meet the percentage criteria for a shortage of storage capacity, we reviewed the data to look for situations where the percentage difference was large, but the absolute difference (in tons) was relatively small. These two counties are also separated below in Table 7.2. We can observe from Table 7.2 that the salt storage capacity in Wayne and Pike counties is only 540 and 520 tons higher than the maximum target stock level, respectively. If usage in these counties grows, then the storage capacities may quickly be insufficient to support a normal ordering pattern and acceptable levels of service.

**Table 7.2 – Counties that have marginal excess storage capacity measured in absolute storage capacity**

| County | Maximum Target Stock Level (Tons) | County Storage Capacity (Tons) | Diference | Percentage |
|---|---|---|---|---|
| Wayne | 1660 | 2200 | 540 | 25 |
| Pike | 1280 | 1800 | 520 | 29 |

Table 7.3 gives a complete listing by county of the storage capacities, maximum target stocks, and percentage and absolute differences.

**Table 7.3 – Summary of storage capacity analysis for all counties**

| District | County | Maximum Target Stock Level (Tons) | County Storage Capacity (Tons) | Diference | Percentage |
|---|---|---|---|---|---|
| 1 | Allen | 1910 | 5900 | 3990 | 68 |
| | Defiance | 1340 | 3500 | 2160 | 62 |
| | Hancock | 2410 | 7400 | 4990 | 67 |
| | Hardin | 1395 | 3250 | 1855 | 57 |
| | Paulding | 1260 | 3150 | 1890 | 60 |
| | Putnam | 1350 | 3500 | 2150 | 61 |
| | Van Wert | 1920 | 4500 | 2580 | 57 |
| | Wyandot | 1790 | 5300 | 3510 | 66 |
| 2 | Fulton | 1180 | 3600 | 2420 | 67 |
| | Henry | 1430 | 3000 | 1570 | 52 |
| | Lucas | 1700 | 2000 | 300 | 15 |
| | Ottawa | 1860 | 3400 | 1540 | 45 |
| | Sandusky | 2010 | 3600 | 1590 | 44 |
| | Seneca | 2200 | 3600 | 1400 | 39 |
| | Williams | 2050 | 3000 | 950 | 32 |
| | Wood | 5030 | 9000 | 3970 | 44 |
| 3 | Ashland | 3780 | 8250 | 4470 | 54 |
| | Crawford | 2550 | 2800 | 250 | 9 |
| | Erie | 2560 | 2200 | -360 | -16 |
| | Huron | 2910 | 5150 | 2240 | 43 |
| | Lorain | 3270 | 6850 | 3580 | 52 |
| | Medina | 5890 | 9650 | 3760 | 39 |
| | Richland | 3470 | 2300 | -1170 | -51 |
| | Wayne | 1660 | 2200 | 540 | 25 |
| 4 | Ashtabula | 14900 | 44000 | 29100 | 66 |
| | Mahoning | 8060 | 22500 | 14440 | 64 |
| | Portage | 6210 | 16550 | 10340 | 62 |
| | Stark | 6180 | 15300 | 9120 | 60 |
| | Summit | 6410 | 20300 | 13890 | 68 |
| | Trumbull | 8220 | 21500 | 13280 | 62 |
| 5 | Coshocton | 2410 | 5300 | 2890 | 55 |
| | Fairfield | 2770 | 5800 | 3030 | 52 |
| | Guernsey | 3540 | 6600 | 3060 | 46 |
| | Knox | 2430 | 4100 | 1670 | 41 |
| | Licking | 2560 | 7400 | 4840 | 65 |
| | Muskingum | 3820 | 7600 | 3780 | 50 |
| | Perry | 2340 | 3400 | 1060 | 31 |

Table 7.3 – Summary of storage capacity analysis for all counties (continued)

| District | County | Maximum Target Stock Level (Tons) | County Storage Capacity (Tons) | Diference | Percentage |
|---|---|---|---|---|---|
| 6 | Delaware | 2720 | 6500 | 3780 | 58 |
| | Fayette | 2940 | 3700 | 760 | 21 |
| | Franklin | 9110 | 22300 | 13190 | 59 |
| | Madison | 3330 | 4860 | 1530 | 31 |
| | Marion | 2210 | 3200 | 990 | 31 |
| | Morrow | 2970 | 4200 | 1230 | 29 |
| | Pickaway | 1480 | 2500 | 1020 | 41 |
| | Union | 3140 | 5400 | 2260 | 42 |
| 7 | Auglaize | 1290 | 2600 | 1310 | 50 |
| | Champaign | 1550 | 2850 | 1300 | 46 |
| | Clark | 2050 | 4330 | 2280 | 53 |
| | Darke | 1630 | 3900 | 2270 | 58 |
| | Logan | 1960 | 4750 | 2790 | 59 |
| | Mercer | 1220 | 4500 | 3280 | 73 |
| | Miami | 1830 | 3832 | 2002 | 52 |
| | Montgomery | 2140 | 6350 | 4210 | 66 |
| | Shelby | 1060 | 4775 | 3715 | 78 |
| 8 | Butler | 1760 | 9200 | 7440 | 81 |
| | Clermont | 3180 | 5900 | 2720 | 46 |
| | Clinton | 3280 | 6700 | 3420 | 51 |
| | Greene | 3150 | 6000 | 2850 | 48 |
| | Hamilton | 4780 | 11825 | 7045 | 60 |
| | Preble | 2890 | 10000 | 7110 | 71 |
| | Warren | 2550 | 5300 | 2750 | 52 |
| 9 | Adams | 1970 | 4300 | 2330 | 54 |
| | Brown | 1850 | 5050 | 3200 | 63 |
| | Highland | 1860 | 4400 | 2540 | 58 |
| | Jackson | 1740 | 3700 | 1960 | 53 |
| | Lawrence | 1190 | 6150 | 4960 | 81 |
| | Pike | 1280 | 1800 | 520 | 29 |
| | Ross | 2680 | 2900 | 220 | 8 |
| | Scioto | 1170 | 3230 | 2060 | 64 |
| 10 | Athens | 1950 | 7500 | 5550 | 74 |
| | Gallia | 1100 | 3500 | 2400 | 69 |
| | Hocking | 1900 | 4000 | 2100 | 53 |
| | Meigs | 1030 | 2200 | 1170 | 53 |
| | Monroe | 1480 | 3500 | 2020 | 58 |
| | Morgan | 1800 | 3000 | 1200 | 40 |
| | Noble | 2730 | 5100 | 2370 | 46 |
| | Vinton | 1690 | 5200 | 3510 | 68 |
| | Washington | 3180 | 7100 | 3920 | 55 |

**Table 7.3 – Summary of storage capacity analysis for all counties (continued)**

| District | County | Maximum Target Stock Level (Tons) | County Storage Capacity (Tons) | Diference | Percentage |
|---|---|---|---|---|---|
| 11 | Belmont | 4130 | 11800 | 7670 | 65 |
| | Carroll | 1700 | 5400 | 3700 | 69 |
| | Columbiana | 3330 | 8550 | 5220 | 61 |
| | Harrison | 2310 | 4200 | 1890 | 45 |
| | Holmes | 1860 | 4200 | 2340 | 56 |
| | Jefferson | 2920 | 8350 | 5430 | 65 |
| | Tuscarawas | 3180 | 6500 | 3320 | 51 |
| 12 | Cuyahoga | 15300 | 26300 | 11000 | 42 |
| | Geauga | 8100 | 15600 | 7500 | 48 |
| | Lake | 5480 | 14150 | 8670 | 61 |

## 7.2. Vendor Storage Capacity Analysis

In the graphs shown below a comparison is made between vendor stockpile capacities, estimated salt for each county according to the contract at the start of fiscal year, and total salt received to the county from the stockpile. The following terms used in the graphs are explained below:

- *Stockpile capacity* is the maximum amount of salt that can be stored by a vendor at a particular stockpile location.
- *County estimated* is the estimated salt usage for each county according to the contract at the start of fiscal year. The data for this is provided in Salt procurement handbook for fiscal year 2006.
- *Total Received* is the amount of salt received by a county during a fiscal year. The data for this analysis was provided at the outset of the project in September 2005.

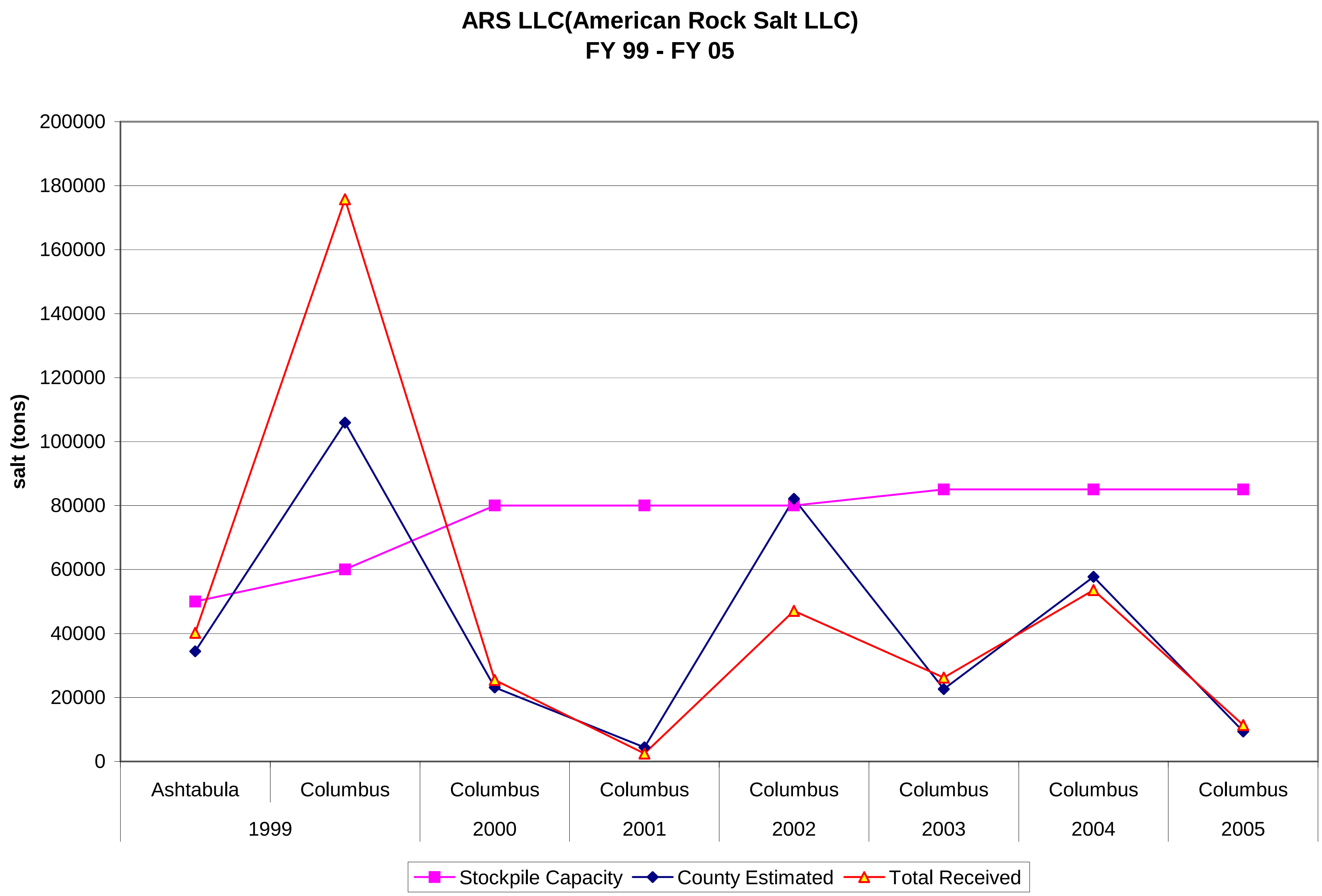



**Figure 7.1 – Comparison of stockpile capacity, estimated usage and total received for ARS**

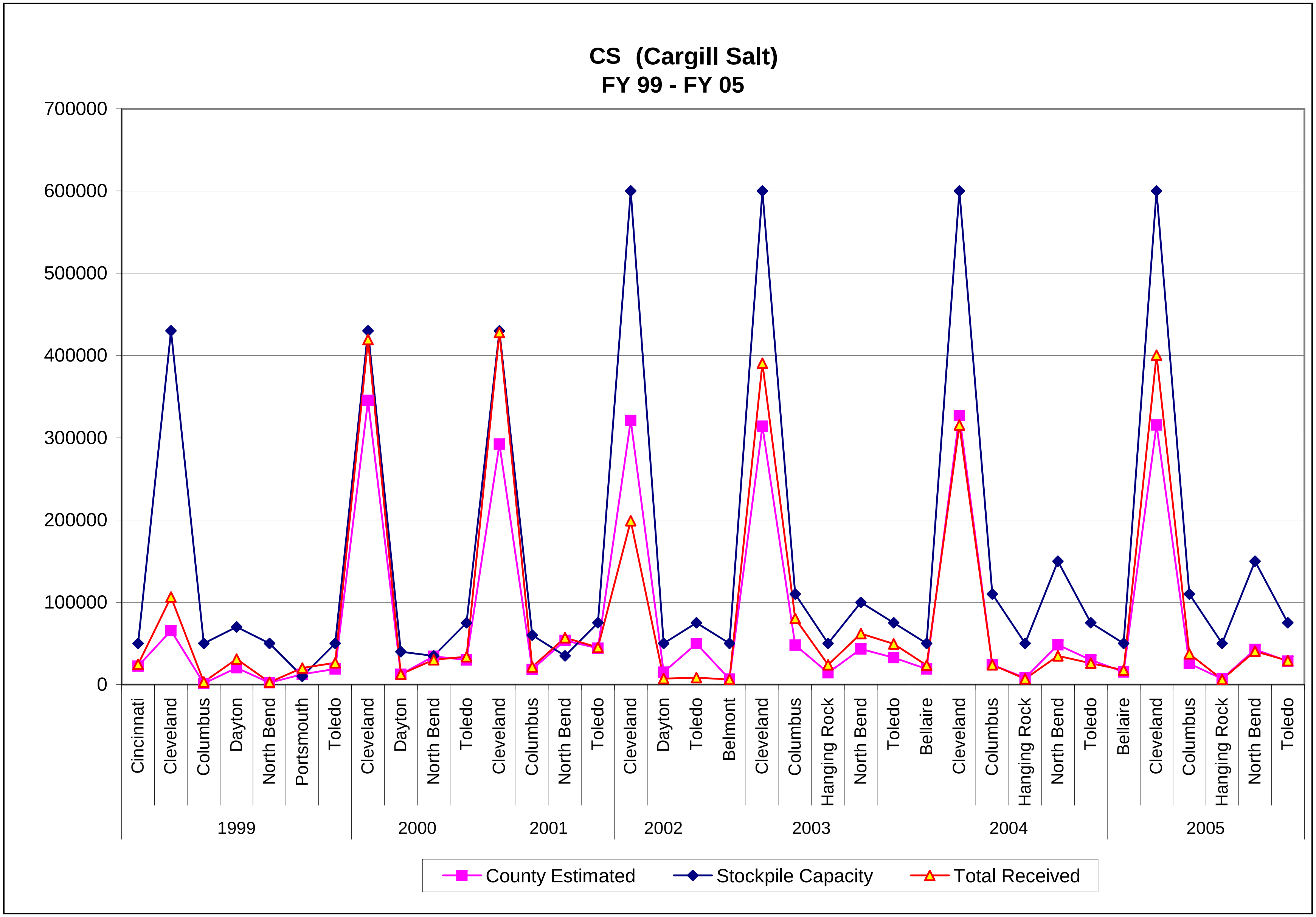

CS (Cargill Salt)
FY 99 - FY 05
700000
600000
500000
400000
300000
200000
100000
0
Cincinnati
Cleveland
Columbus
Dayton
North Bend
Portsmouth
Toledo
Cleveland
Dayton
North Bend
Toledo
Cleveland
Columbus
North Bend
Toledo
Cleveland
Dayton
Toledo
Belmont
Cleveland
Columbus
Hanging Rock
North Bend
Toledo
Bellaire
Cleveland
Columbus
Hanging Rock
North Bend
Toledo
Bellaire
Cleveland
Columbus
Hanging Rock
North Bend
Toledo
1999
2000
2001
2002
2003
2004
2005
County Estimated
Stockpile Capacity
Total Received

**Figure 7.2 - Comparison of stockpile capacity, estimated usage and total received for CS**

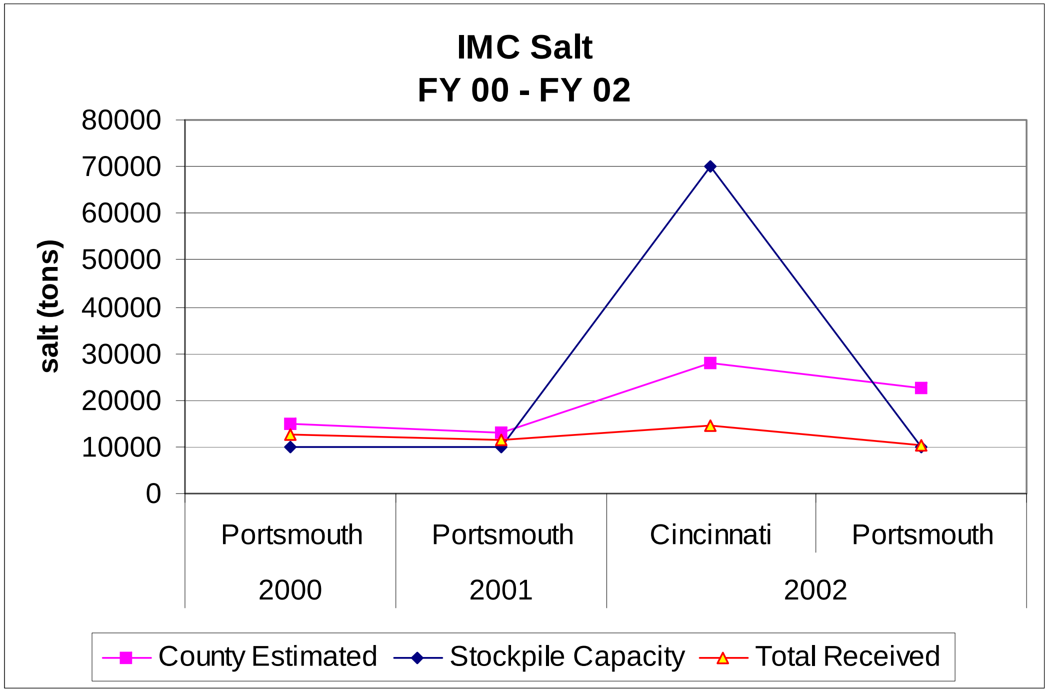



**Figure 7.3 - Comparison of stockpile capacity, estimated usage and total received for IMC**

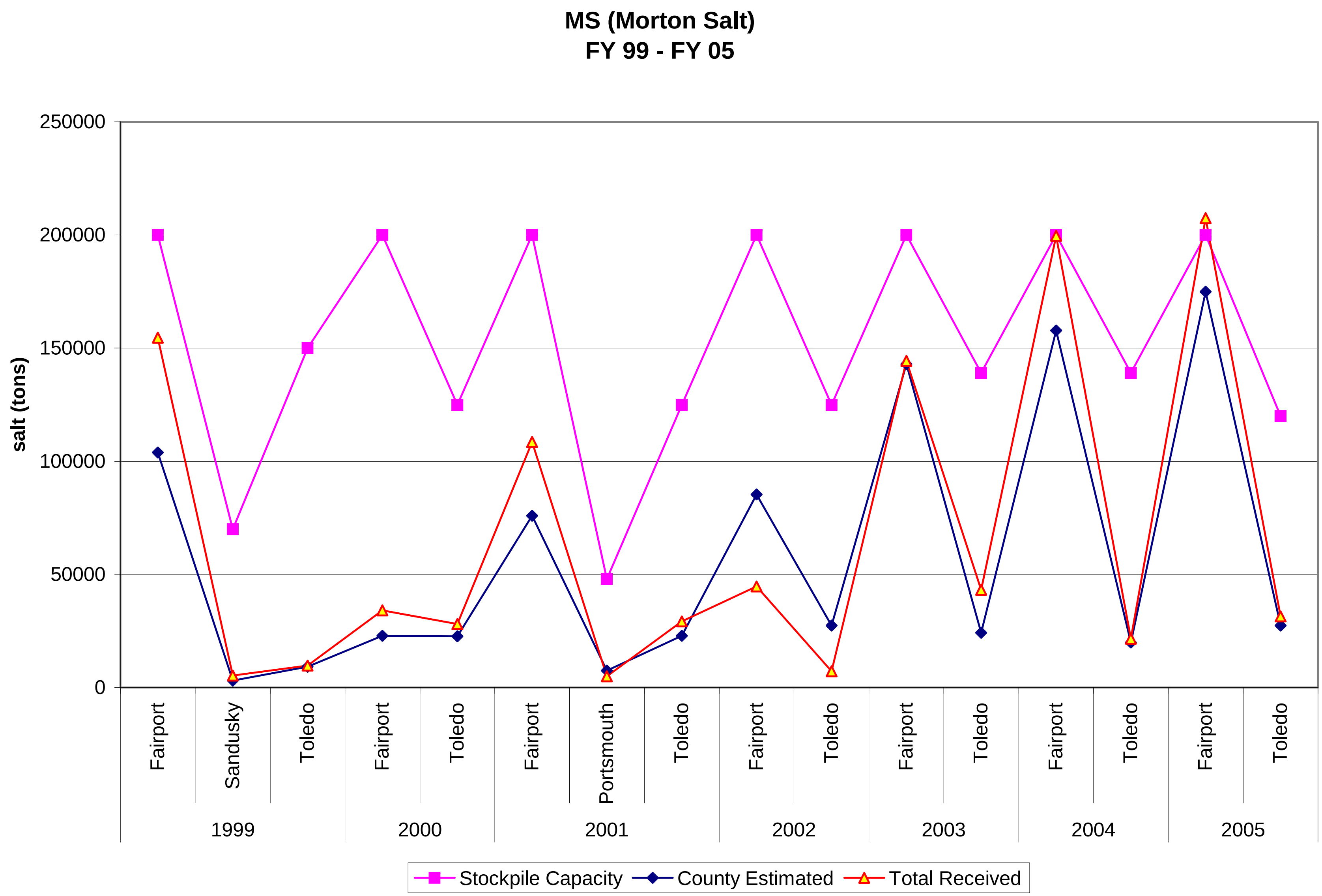



**Figure 7.4 - Comparison of stockpile capacity, estimated usage and total received for MS**

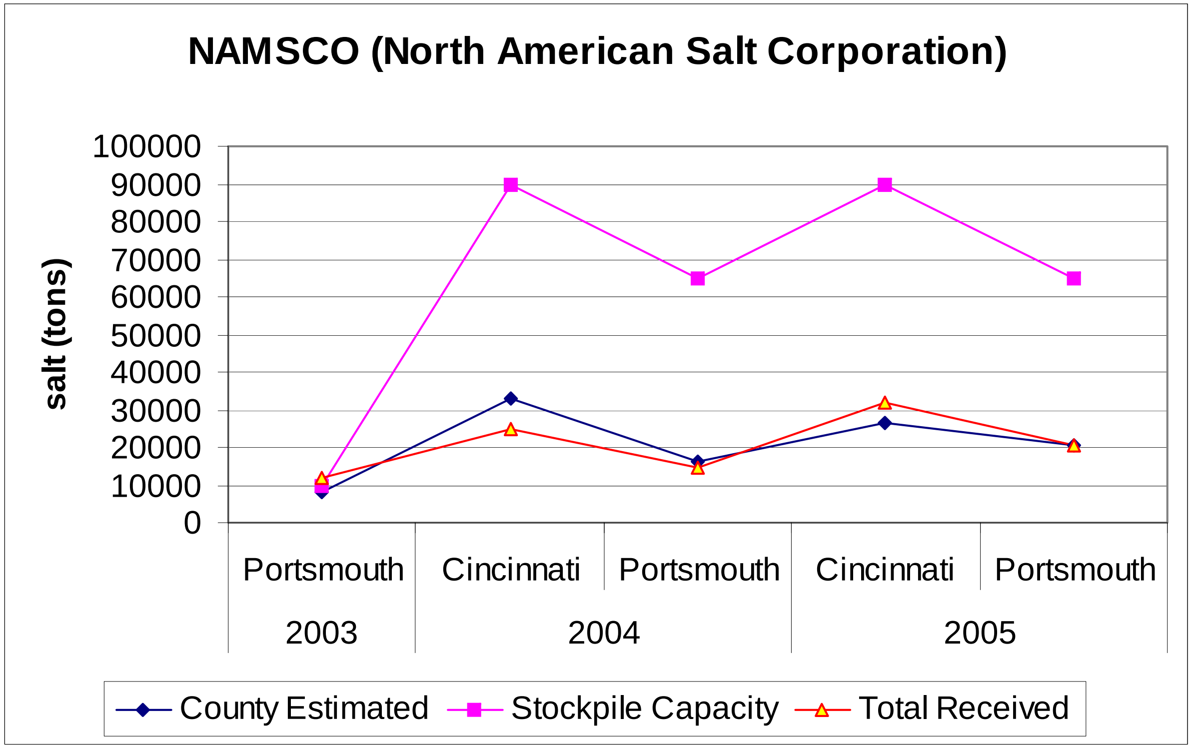



**Figure 7.5 Comparison of stockpile capacity, estimated usage and total received for NAMSCO**

## 7.3. Inventory Measurement Technologies

A central finding of our review of the practice of supply chain management in other industries is that accurate visibility of inventory levels, both locally and at the county and state level, is critical to effective management of inventories. "Visibility" refers to the availability of accurate and timely information on the status of inventories at each storage location. Accuracy is important because to implement the (R, S) guidelines, it is important to have an appropriately accurate measure of the inventory level, so that orders can be placed once inventory crosses the re-order point as it is being used. Timely information is important because order placement will be delayed when there is a time lag in the detection of the inventory crossing the re-order point as it is depleted. Without timely and accurate information on inventory status, and an effective order placement procedure, the probability of stockout will increase beyond those predicted by the models in this report.

As a general principle in inventory management, the timely placement of orders is critical to maintaining a high level of service, and to operate with minimal cost. In the inventory literature and the modern practice of inventory management many technologies have been described and put into place to improve inventory monitoring and ordering. In companies such as Wal-Mart and Kroger, automatic tracking of stocks is enabled through point-of-sale monitoring and use of technologies such as bar-code scanners, and more recently RFID (radio-frequency-identification). In the retail and grocery industries, these technologies enable automated ordering based on order-point and inventory target guidelines such as those developed for ODOT in this project. In some cases, the information in the computing systems from this detection technology is shared with vendors to allow them to have a real-time tracing of product usage and imminent orders. This approach enables lower inventories because ordering occurs in close connection to actual inventory status. In the automotive and other manufacturing industries, re-order-points are often tracked through the use of "kanban" techniques or inventory monitoring "cards". These techniques fill the role of establishing planned re-order points and then having a systematic process that places the orders.

The tracking of inventory and timely placement of orders is particularly important during times of high usage in the winter maintenance context, when levels of activity at the county garages are very high. Any technology that can be used to automatically track inventory status, and update this information in the ODOT databases would be helpful in controlling salt stocks effectively.

The goals of the project in this dimension were limited: We will review some ideas for a basic design and technology that could track inventory status. A more detailed study will be required to fully design, prototype and test a system for monitoring, transmitting and recording the salt status at critical locations. Our recommendation is, after further development and study, that this type of technology be initially considered for locations that are deemed "critical" in terms of monitoring of salt stocks. A full development of the technology would require integration into ODOT's information technology infrastructure, so that inventory status could be transmitted directly into ODOT's information systems.

As part of the future prototyping exercise, it must be determined if the sensors chosen can withstand the dusty and corrosive environment within a typical salt dome and continue to perform adequately. In some cases electrical service may not be available at the salt dome, adding to the expense of such a system. Overall, a fielded system must prove to be an accurate measure of inventory level that is more effective than a visual inspection by an employee on-site.

With a view towards a collaborative relationship with suppliers, continuous measurement of inventory status would be necessary to provide a supplier with an accurate inventory status for a vendor-managed-inventory or similar arrangement where the supplier has significant responsibility for monitoring and maintaining sufficient inventory at the county locations.

In our research, we found a variety of technologies for accurately measuring the volume of a moving pile of material. For example, in the mining industry, systems are available with sensors that are used to measure mined material moving on a conveyor. These systems use a sensor and computers to map the three dimensional surface of the moving pile as it moves past the sensor. These systems are complex and expensive. Furthermore, getting a three dimensional model of a surface in these systems currently requires the material to be moving. Because of the expense, complexity and environment required this type of system would be infeasible for salt stockpile measurement.

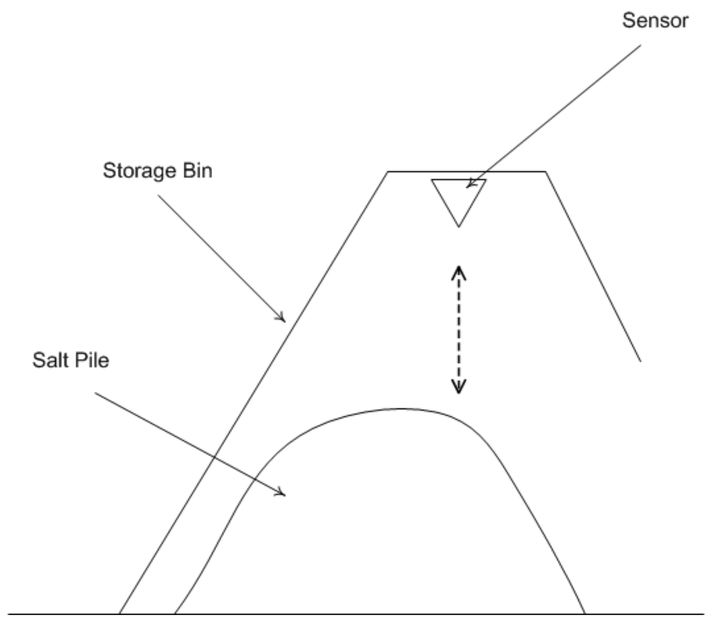



**Figure 7.6 - Schematic of design I of sensor setup for salt pile measurement**

Figure 7.6 shows one design (design I) of a potential setup for a pile measurement technology. Rather than mapping the detailed surface of the pile, and from that determining a volume, this design is intended to measure the height of the pile. The type of sensor used could be based on radar or laser technology, using a time-of-flight protocol to measure the distance from the sensor to the top of the pile. The sensor would be mounted at the top of the storage bin, looking down on the tip of the pile. The sensor emits an energy pulse (radar or laser) and its time-of-flight from the sensor to the reflecting surface of the pile back to the sensor is used to measure the distance. This information would be transmitted back to a computer database, where the distance measure could be translated into an approximate volume in the pile. This type of design is common in grain silos and other similar applications.

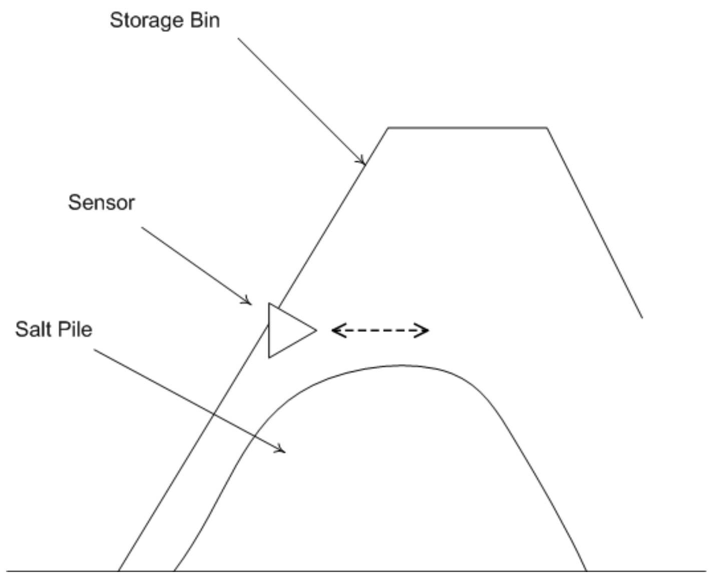



**Figure 7.7 - Schematic of design II of sensor setup for salt pile measurement**

Figure 7.7 shows an alternate design, that could employ a less expensive sensor, but that would also provide less information. In this design, the sensor is mounted on the side of the storage bin, rather than at the top. By looking at the pile from the side, the detector would simply indicate whether the height of the pile had fallen below a specified level, but would not give a continuous measurement of pile height. The sensor could be less sensitive, since it must only indicate the presence or absence of a reflecting surface at the appropriate distance, rather than a continuous measure of the distance of the reflecting surface from the sensor. This design would also require less calibration for each installation, since the distance from the sensor does not need to be translated into a volume estimate. A drawback of this design is that lacking a continuous measure of inventory status is not as useful from the inventory control perspective.

Finally, one possible way of leveraging the regression model described earlier is to use the predictions from the regression model as an estimate of usage in each county. These usage estimates could be available as soon as the daily weather variables are posted on the NOAA websites. These estimates could be shared with suppliers on a daily or weekly basis to give a preliminary estimate, as to where salt is being used at the highest rates. With more information, even if it is an estimate, the salt vendors could more effectively allocate their stocks and support the State's level of service goals.

# 8. Conclusion, Implementation and Future Work

The ($R$, $S$)-inventory guideline allows the inventory manager to make systematic decisions about when to order and how to much order. Orders in this inventory guideline are made at a predefined point based on the reorder point, $R$. The order amount is determined by the target level and current inventory level. In this study, we related these guidelines to the actual historical usage of salt in the Ohio counties. We also made a detailed county-by-county comparison with the 10 day maximum usage guideline from the ODOT maintenance administration manual. The conclusions of this analysis and comparison were:

For the following counties, the 10 day maximum usage significantly larger than the suggested inventory targets: Wood, Preble, Muskingum, and Butler. For these counties, our analysis indicates that significantly less than the 10-day max usage may be sufficient as an inventory target. It may be possible to reduce the inventories in these counties without a negative service level impact.

For the following counties, the 10 day maximum usage is moderately larger than the suggested inventory targets: Montgomery, Fairfield, Licking, Hancock, Monroe, Auglaize, Stark, Lucas, Holmes, Franklin, Shelby, Columbiana and Ashland. For these counties, our analysis indicates considering a moderate decrease in inventory will not negatively impact an adequate level of service.

In both cases, the decision to decrease inventory levels should be balanced with any additional practical issues not considered explicitly in this report.

For the following counties, the 10 day maximum usage is moderately smaller than the suggested inventory targets: Medina, Madison, Union, Richland and Tuscarawas. For these counties our analysis indicates that considering a moderate increase in the inventory levels is necessary to maintain an adequate level of service.

For the following counties, the 10 day maximum usage is significantly smaller than the suggested inventory targets: Ashtabula, Geauga and Cuyahoga. For these counties, our analysis indicates that significantly more than the 10-day max usage may be necessary as an inventory target. It is likely that increasing the inventories in these counties can improve the level of service. It is worth noting that all three of these counties have among the highest overall usage in the state. If deliveries from the vendors to these counties are more reliable than to other counties because of the regularity of delivery and the volume of orders, then the 10 day max may be acceptable as an inventory target.

In all of the other county studies, the difference between our suggested inventory target and the 10 day maximum usage was relatively small. We recommend that no change be made in the inventory guideline for these counties. Of course, the suggested inventory targets and re-order points can be used to guide ordering for all counties.

The suggested inventory targets were also compared to the reported storage capacities in each county as of September 2007. Based on this comparison we identified counties that had a significant storage deficiency (Richland and Erie). Changes in storage capacity since this time have increased the storage capacity in the two counties identified. We also identified counties that had a marginally acceptable storage capacity, both on an absolute basis as well as a percentage basis (Lucas, Crawford and Ross). This analysis will support focusing on these counties as salt usage increases. Overall, our methodology of comparing capacities to order targets has been adopted as one of the standard features of ODOT's monthly Salt Usage reporting.

From a research perspective, the main products of this project are:

- A review of background literature on inventory management guidelines and supply chain management practices that are relevant to the management of winter maintenance materials.
- A review of current trends in supplier-buyer relationships in industry that help support high levels of service for serving customer demands.
- A regression model methodology to predict the usage of salt in a county based on the weather reported via daily NOAA reports for the major city in that county.
- A methodology for using those models, together with a lane-mile adjustment and a weather zone assignment, to make salt usage predictions for counties that do not contain a major city.
- A framework for using the salt usage prediction from these models, or raw usage data from the counties, to develop (R, S) inventory control guidelines that satisfy a given level of service and minimize the stock required to achieve that level of service.
- Specific analysis for each of the 88 Ohio counties that develops the (R, S) parameters for each county, for each month of the winter season.
- A simulation study to help guide the implementation of the (R, S) guidelines. The results of this study provide guidelines for implementing some of the current practices in inventory ordering together with the suggested (R, S) guidelines. This includes how to transition the guidelines from month to month through the winter season and still achieve the designed levels of service.
- A comparison via simulation of the pattern of orders that are generated using the suggested (R, S) guidelines, vs the actual pattern of orders. This comparison would be useful to share with

suppliers to help understand how the implementation of the new guidelines would affect the orders they receive.

- A study of the storage capacities in each county, as they relate to usage and the suggested (R, S) inventory guidelines. Counties with marginal or insufficient storage capacity to sustain high levels of service or acceptable delivery frequencies have been identified.
- A study of the storage capacities of salt vendors, as it relates to their commitments in the state contract, as well as compared to the actual usage.
- A preliminary review of possible designs for inventory tracking technologies to provide visibility of inventory levels for replenishment purposes.

Some of the major conclusions drawn from the model development and analysis listed above include:

In practice it is difficult to track inventory when the supply is not carefully monitored. A topic of future study is how inaccuracy in inventory tracking affects the inventory guideline. Implementation of the guidelines developed in this report requires a study of how to split the guideline values provided over counties that have multiple garages. These models were developed at the county level and many counties have more then one garage. Future research would study how to effectively split the results from a county model over individual garages. This is an important study because garages track and order salt individually. There is an opportunity to share the methodology detailed in this report with other states with significant snow operations in order to develop ordering guidelines.

Future work should also study the further development of inventory tracking technologies. This could be accomplished through the use of sensors that detect inventory status at the storage bins, and automatically transmit this information back to the ODOT information infrastructure. Alternatively, the regression models developed in this project could be used to estimate the rate of usage as the weather information in each county becomes available, and this information could be used until actual usage has been recorded manually using current practices.

Future work that builds on the results of this project also includes the consideration of tactics for an increasingly collaborative relationship with suppliers through the appropriate sharing of information and risks. Through this enhanced collaborative approach, the suppliers will have the incentive and the tools to provide the highest levels of service to the State of Ohio.

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# Appendix 1: (*R*, *S*) Guideline Parameters for All Ohio Counties by District

**(in tons)**

## District 1

| Allen County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 395 | 1120 | 1090 | 846 | 806 |
| 2 | µLT | 43.0 | 312 | 413 | 220 | 142 |
| 3 = 1 + 2 | R | 438 | 1430 | 1500 | 1070 | 948 |
| 4 | E(week) | 43.0 | 312 | 413 | 220 | 142 |
| 5 = 3 + 4 | S | 481 | 1740 | 1910 | 1290 | 1090 |

| Defiance County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 243 | 597 | 768 | 418 | 471 |
| 2 | µLT | 25.3 | 169 | 285 | 147 | 98.2 |
| 3 = 1 + 2 | R | 269 | 765 | 1050 | 564 | 569 |
| 4 | E(week) | 25.3 | 169 | 285 | 147 | 98.2 |
| 5 = 3 + 4 | S | 294 | 934 | 1340 | 711 | 668 |

| Hancock County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 618 | 1170 | 1330 | 722 | 913 |
| 2 | µLT | 65.7 | 374 | 541 | 236 | 196 |
| 3 = 1 + 2 | R | 683 | 1550 | 1870 | 957 | 1110 |
| 4 | E(week) | 65.7 | 374 | 541 | 236 | 196 |
| 5 = 3 + 4 | S | 749 | 1920 | 2410 | 1190 | 1300 |

| Hardin County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 358 | 646 | 779 | 511 | 539 |
| 2 | µLT | 32.0 | 205 | 308 | 171 | 95.5 |
| 3 = 1 + 2 | R | 390 | 851 | 1087 | 682 | 634 |
| 4 | E(week) | 32.0 | 205 | 308 | 171 | 95.5 |
| 5 = 3 + 4 | S | 422 | 1056 | 1395 | 853 | 730 |

| Paulding County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 162 | 568 | 725 | 473 | 489 |
| 2 | µLT | 18.1 | 168 | 270 | 150 | 97.9 |
| 3 = 1 + 2 | R | 180 | 736 | 995 | 623 | 587 |
| 4 | E(week) | 18.1 | 168 | 270 | 150 | 97.9 |
| 5 = 3 + 4 | S | 198 | 904 | 1260 | 773 | 685 |

| Putnam County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 309 | 705 | 772 | 549 | 512 |
| 2 | µLT | 33.7 | 213 | 287 | 149 | 101 |
| 3 = 1 + 2 | R | 342 | 918 | 1060 | 697 | 613 |
| 4 | E(week) | 33.7 | 213 | 287 | 149 | 101 |
| 5 = 3 + 4 | S | 376 | 1130 | 1350 | 846 | 715 |

| Van Wert County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 216 | 976 | 1070 | 761 | 777 |
| 2 | µLT | 32 | 291 | 425 | 227 | 146 |
| 3 = 1 + 2 | R | 248 | 1270 | 1500 | 988 | 923 |
| 4 | E(week) | 32 | 291 | 425 | 227 | 146 |
| 5 = 3 + 4 | S | 279 | 1560 | 1920 | 1220 | 1070 |

| Wyandot County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 332 | 661 | 1030 | 522 | 596 |
| 2 | µLT | 35.8 | 251 | 384 | 215 | 120 |
| 3 = 1 + 2 | R | 368 | 912 | 1410 | 737 | 716 |
| 4 | E(week) | 35.8 | 251 | 384 | 215 | 120 |
| 5 = 3 + 4 | S | 404 | 1160 | 1790 | 951 | 836 |

# District 2

| Fulton County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 77.6 | 658 | 639 | 529 | 499 |
| 2 | µLT | 11.6 | 204 | 272 | 183 | 111 |
| 3 = 1 + 2 | R | 89.2 | 862 | 911 | 712 | 610 |
| 4 | E (week) | 11.6 | 204 | 272 | 183 | 111 |
| 5 = 3 + 4 | S | 101 | 1070 | 1180 | 895 | 720 |

| Henry County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 139 | 886 | 763 | 572 | 799 |
| 2 | µLT | 16 | 270 | 316 | 183 | 148 |
| 3 = 1 + 2 | R | 155 | 1160 | 1080 | 755 | 947 |
| 4 | E (week) | 16 | 270 | 316 | 183 | 148 |
| 5 = 3 + 4 | S | 171 | 1430 | 1390 | 938 | 1100 |

| Lucas County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 78.8 | 1000 | 1070 | 600 | 669 |
| 2 | µLT | 9.31 | 292 | 315 | 162 | 140 |
| 3 = 1 + 2 | R | 88.1 | 1290 | 1380 | 762 | 808 |
| 4 | E (week) | 9.31 | 292 | 315 | 162 | 140 |
| 5 = 3 + 4 | S | 97.4 | 1590 | 1700 | 925 | 948 |

| Ottawa County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 143 | 901 | 1020 | 801 | 760 |
| 2 | µLT | 16.5 | 293 | 422 | 279 | 166 |
| 3 = 1 + 2 | R | 159 | 1190 | 1440 | 1080 | 926 |
| 4 | E (week) | 16.5 | 293 | 422 | 279 | 166 |
| 5 = 3 + 4 | S | 176 | 1490 | 1860 | 1360 | 1090 |

| Sandusky County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 287 | 956 | 1140 | 723 | 746 |
| 2 | µLT | 30.7 | 299 | 437 | 235 | 178 |
| 3 = 1 + 2 | R | 318 | 1260 | 1580 | 958 | 923 |
| 4 | E (week) | 30.7 | 299 | 437 | 235 | 178 |
| 5 = 3 + 4 | S | 349 | 1550 | 2010 | 1190 | 1100 |

| Seneca County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 414 | 1090 | 1250 | 733 | 837 |
| 2 | µLT | 45.6 | 387 | 472 | 278 | 189 |
| 3 = 1 + 2 | R | 459 | 1470 | 1720 | 1010 | 1030 |
| 4 | E (week) | 45.6 | 387 | 472 | 278 | 189 |
| 5 = 3 + 4 | S | 505 | 1860 | 2200 | 1290 | 1210 |

| Williams County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 194 | 1080 | 1140 | 699 | 758 |
| 2 | µLT | 28.5 | 320 | 458 | 266 | 159 |
| 3 = 1 + 2 | R | 223 | 1400 | 1590 | 965 | 918 |
| 4 | E (week) | 28.5 | 320 | 458 | 266 | 159 |
| 5 = 3 + 4 | S | 252 | 1720 | 2050 | 1230 | 1080 |

| Wood County | | | | | | |
|---|---|---|---|---|---|---|
| Months | 0 | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 561 | 2640 | 2850 | 1880 | 2350 |
| 2 | µLT | 62 | 826 | 1090 | 650 | 512 |
| 3 = 1 + 2 | R | 623 | 3460 | 3940 | 2530 | 2860 |
| 4 | E(week) | 62 | 826 | 1090 | 650 | 512 |
| 5 = 3 + 4 | S | 685 | 4290 | 5030 | 3190 | 3380 |

# District 3

| Ashland County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 621 | 1780 | 1980 | 1480 | 1340 |
| 2 | µLT | 95.6 | 695 | 901 | 603 | 363 |
| 3 = 1 + 2 | R | 717 | 2480 | 2880 | 2090 | 1710 |
| 4 | E (week) | 95.6 | 695 | 901 | 603 | 363 |
| 5 = 3 + 4 | S | 812 | 3170 | 3780 | 2690 | 2070 |

| Crawford County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 531 | 1250 | 1330 | 882 | 962 |
| 2 | µLT | 64.6 | 438 | 610 | 345 | 219 |
| 3 = 1 + 2 | R | 596 | 1690 | 1940 | 1230 | 1180 |
| 4 | E (week) | 64.6 | 438 | 610 | 345 | 219 |
| 5 = 3 + 4 | S | 660 | 2130 | 2550 | 1570 | 1400 |

| Erie County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 316 | 1150 | 1380 | 930 | 660 |
| 2 | µLT | 40.3 | 448 | 591 | 333 | 208 |
| 3 = 1 + 2 | R | 357 | 1600 | 1970 | 1260 | 867 |
| 4 | E (week) | 40.3 | 448 | 591 | 333 | 208 |
| 5 = 3 + 4 | S | 397 | 2050 | 2560 | 1600 | 1070 |

| Huron County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 337 | 1220 | 1540 | 1050 | 1050 |
| 2 | µLT | 41.8 | 484 | 686 | 422 | 271 |
| 3 = 1 + 2 | R | 379 | 1700 | 2230 | 1470 | 1320 |
| 4 | E (week) | 41.8 | 484 | 686 | 422 | 271 |
| 5 = 3 + 4 | S | 420 | 2180 | 2910 | 1890 | 1590 |

| Lorain County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 531 | 1890 | 1740 | 1840 | 1320 |
| 2 | µLT | 64.9 | 665 | 766 | 649 | 418 |
| 3 = 1 + 2 | R | 595 | 2560 | 2500 | 2490 | 1740 |
| 4 | E (week) | 64.9 | 665 | 766 | 649 | 418 |
| 5 = 3 + 4 | S | 660 | 3220 | 3270 | 3140 | 2150 |

| Medina County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 974 | 2490 | 3130 | 2130 | 2040 |
| 2 | µLT | 148 | 976 | 1380 | 891 | 574 |
| 3 = 1 + 2 | R | 1120 | 3460 | 4510 | 3020 | 2610 |
| 4 | E (week) | 148 | 976 | 1380 | 891 | 574 |
| 5 = 3 + 4 | S | 1270 | 4440 | 5890 | 3910 | 3180 |

| Richland County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 666 | 1830 | 1780 | 1410 | 1270 |
| 2 | µLT | 100 | 650 | 845 | 546 | 301 |
| 3 = 1 + 2 | R | 766 | 2480 | 2620 | 1960 | 1570 |
| 4 | E (week) | 100 | 650 | 845 | 546 | 301 |
| 5 = 3 + 4 | S | 866 | 3130 | 3470 | 2500 | 1870 |

| Wayne County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 216 | 911 | 864 | 766 | 610 |
| 2 | µLT | 29.1 | 334 | 400 | 262 | 155 |
| 3 = 1 + 2 | R | 245 | 1250 | 1260 | 1030 | 764 |
| 4 | E (week) | 29.1 | 334 | 400 | 262 | 155 |
| 5 = 3 + 4 | S | 274 | 1580 | 1660 | 1290 | 919 |

# District 4

| Ashtabula County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 3790 | 6370 | 7550 | 4500 | 3900 |
| 2 | µLT | 543 | 2730 | 3680 | 2080 | 1370 |
| 3 = 1 + 2 | R | 4340 | 9090 | 11200 | 6580 | 5270 |
| 4 | E (week) | 543 | 2730 | 3680 | 2080 | 1370 |
| 5 = 3 + 4 | S | 4880 | 11800 | 14900 | 8660 | 6640 |

| Mahoning County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 1270 | 3200 | 4240 | 2810 | 2330 |
| 2 | µLT | 198 | 1190 | 1910 | 1100 | 615 |
| 3 = 1 + 2 | R | 1470 | 4390 | 6150 | 3910 | 2950 |
| 4 | E (week) | 198 | 1190 | 1910 | 1100 | 615 |
| 5 = 3 + 4 | S | 1670 | 5580 | 8060 | 5010 | 3560 |

| Portage County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 912 | 2440 | 3400 | 1940 | 1890 |
| 2 | µLT | 141 | 932 | 1400 | 804 | 508 |
| 3 = 1 + 2 | R | 1050 | 3370 | 4800 | 2740 | 2400 |
| 4 | E (week) | 141 | 932 | 1400 | 804 | 508 |
| 5 = 3 + 4 | S | 1190 | 4300 | 6210 | 3540 | 2910 |

| Stark County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 796 | 3000 | 3400 | 1760 | 1750 |
| 2 | µLT | 105 | 1000 | 1390 | 680 | 407 |
| 3 = 1 + 2 | R | 902 | 4000 | 4790 | 2440 | 2150 |
| 4 | E (week) | 105 | 1000 | 1390 | 680 | 407 |
| 5 = 3 + 4 | S | 1010 | 5010 | 6180 | 3120 | 2560 |

| Summit County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 863 | 2890 | 3250 | 2010 | 2650 |
| 2 | µLT | 149 | 1150 | 1580 | 889 | 705 |
| 3 = 1 + 2 | R | 1010 | 4040 | 4830 | 2890 | 3350 |
| 4 | E (week) | 149 | 1150 | 1580 | 889 | 705 |
| 5 = 3 + 4 | S | 1160 | 5190 | 6410 | 3780 | 4060 |

| Trumbull County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 1370 | 4150 | 4460 | 2820 | 2870 |
| 2 | µLT | 236 | 1460 | 1880 | 1170 | 724 |
| 3 = 1 + 2 | R | 1610 | 5610 | 6340 | 3990 | 3600 |
| 4 | E (week) | 236 | 1460 | 1880 | 1170 | 724 |
| 5 = 3 + 4 | S | 1850 | 7070 | 8220 | 5160 | 4320 |

# District 5

| Coshocton County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 146 | 915 | 1380 | 751 | 527 |
| 2 | μLT | 18.8 | 253 | 511 | 205 | 90.6 |
| 3 = 1 + 2 | R | 165 | 1170 | 1900 | 956 | 617 |
| 4 | E (week) | 18.8 | 253 | 511 | 205 | 90.6 |
| 5 = 3 + 4 | S | 184 | 1420 | 2410 | 1160 | 708 |

| Fairfield County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 279 | 958 | 1520 | 1160 | 585 |
| 2 | μLT | 35.6 | 290 | 623 | 304 | 98 |
| 3 = 1 + 2 | R | 315 | 1250 | 2140 | 1470 | 683 |
| 4 | E (week) | 35.6 | 290 | 623 | 304 | 98 |
| 5 = 3 + 4 | S | 351 | 1540 | 2770 | 1770 | 781 |

| Guernsey County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 223 | 1310 | 1910 | 1220 | 680 |
| 2 | μLT | 28.2 | 341 | 814 | 316 | 135 |
| 3 = 1 + 2 | R | 251 | 1650 | 2720 | 1530 | 815 |
| 4 | E (week) | 28.2 | 341 | 814 | 316 | 135 |
| 5 = 3 + 4 | S | 279 | 1990 | 3540 | 1850 | 950 |

| Knox County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 333 | 887 | 1380 | 959 | 614 |
| 2 | μLT | 46.4 | 283 | 525 | 271 | 126 |
| 3 = 1 + 2 | R | 379 | 1170 | 1910 | 1230 | 741 |
| 4 | E (week) | 46.4 | 283 | 525 | 271 | 126 |
| 5 = 3 + 4 | S | 426 | 1450 | 2430 | 1500 | 867 |

| Licking County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 282 | 897 | 1460 | 899 | 685 |
| 2 | μLT | 34.6 | 281 | 551 | 249 | 126 |
| 3 = 1 + 2 | R | 316 | 1180 | 2010 | 1150 | 811 |
| 4 | E (week) | 34.6 | 281 | 551 | 249 | 126 |
| 5 = 3 + 4 | S | 351 | 1460 | 2560 | 1400 | 938 |

| Muskingum County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 352 | 1500 | 2230 | 1150 | 901 |
| 2 | μLT | 39.8 | 398 | 795 | 308 | 142 |
| 3 = 1 + 2 | R | 392 | 1900 | 3030 | 1460 | 1040 |
| 4 | E (week) | 39.8 | 398 | 795 | 308 | 142 |
| 5 = 3 + 4 | S | 432 | 2300 | 3820 | 1770 | 1180 |

| Perry County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 244 | 793 | 1280 | 853 | 398 |
| 2 | μLT | 28.5 | 222 | 529 | 215 | 79 |
| 3 = 1 + 2 | R | 273 | 1020 | 1810 | 1070 | 477 |
| 4 | E (week) | 28.5 | 222 | 529 | 215 | 79 |
| 5 = 3 + 4 | S | 301 | 1240 | 2340 | 1280 | 556 |

# District 6

| Delaware County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 425 | 1070 | 1510 | 1060 | 698 |
| 2 | µLT | 45.1 | 326 | 607 | 278 | 154 |
| 3 = 1 + 2 | R | 470 | 1400 | 2120 | 1340 | 851 |
| 4 | E (week) | 45.1 | 326 | 607 | 278 | 154 |
| 5 = 3 + 4 | S | 515 | 1720 | 2720 | 1610 | 1000 |

| Fayette County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 111 | 1000 | 1670 | 1030 | 584 |
| 2 | µLT | 14.1 | 259 | 633 | 248 | 90.8 |
| 3 = 1 + 2 | R | 125 | 1260 | 2300 | 1280 | 675 |
| 4 | E (week) | 14.1 | 259 | 633 | 248 | 90.8 |
| 5 = 3 + 4 | S | 139 | 1520 | 2940 | 1530 | 766 |

| Franklin County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 739 | 3280 | 5200 | 4120 | 1660 |
| 2 | µLT | 82.7 | 960 | 1950 | 908 | 360 |
| 3 = 1 + 2 | R | 822 | 4240 | 7150 | 5020 | 2020 |
| 4 | E (week) | 82.7 | 960 | 1950 | 908 | 360 |
| 5 = 3 + 4 | S | 905 | 5200 | 9110 | 5930 | 2380 |

| Madison County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 208 | 1160 | 1770 | 1090 | 635 |
| 2 | µLT | 31.5 | 351 | 777 | 335 | 133 |
| 3 = 1 + 2 | R | 239 | 1510 | 2550 | 1430 | 768 |
| 4 | E (week) | 31.5 | 351 | 777 | 335 | 133 |
| 5 = 3 + 4 | S | 271 | 1860 | 3330 | 1760 | 902 |

| Marion County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 607 | 945 | 1170 | 708 | 567 |
| 2 | µLT | 64.3 | 348 | 522 | 252 | 118 |
| 3 = 1 + 2 | R | 671 | 1290 | 1690 | 959 | 685 |
| 4 | E (week) | 64.3 | 348 | 522 | 252 | 118 |
| 5 = 3 + 4 | S | 735 | 1640 | 2210 | 1210 | 803 |

| Morrow County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 536 | 1280 | 1620 | 996 | 990 |
| 2 | µLT | 80 | 455 | 676 | 344 | 201 |
| 3 = 1 + 2 | R | 616 | 1730 | 2300 | 1340 | 1190 |
| 4 | E (week) | 80 | 455 | 676 | 344 | 201 |
| 5 = 3 + 4 | S | 696 | 2190 | 2970 | 1680 | 1390 |

| Pickaway County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 57.9 | 469 | 785 | 451 | 272 |
| 2 | µLT | 5.36 | 141 | 346 | 134 | 47.3 |
| 3 = 1 + 2 | R | 63.2 | 610 | 1130 | 585 | 319 |
| 4 | E (week) | 5.36 | 141 | 346 | 134 | 47.3 |
| 5 = 3 + 4 | S | 68.6 | 751 | 1480 | 719 | 367 |

| Union County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 555 | 1020 | 1710 | 1090 | 778 |
| 2 | µLT | 60.4 | 324 | 717 | 287 | 168 |
| 3 = 1 + 2 | R | 615 | 1350 | 2420 | 1380 | 946 |
| 4 | E (week) | 60.4 | 324 | 717 | 287 | 168 |
| 5 = 3 + 4 | S | 676 | 1670 | 3140 | 1660 | 1110 |

# District 7

| Auglaize County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 156 | 588 | 774 | 435 | 431 |
| 2 | µLT | 18.5 | 168 | 260 | 121 | 97.6 |
| 3 = 1 + 2 | R | 174 | 756 | 1030 | 555 | 529 |
| 4 | E (week) | 18.5 | 168 | 260 | 121 | 97.6 |
| 5 = 3 + 4 | S | 193 | 924 | 1290 | 676 | 627 |

| Champaign County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 132 | 599 | 871 | 583 | 392 |
| 2 | µLT | 15.3 | 163 | 338 | 173 | 80.6 |
| 3 = 1 + 2 | R | 148 | 763 | 1210 | 755 | 473 |
| 4 | E (week) | 15.3 | 163 | 338 | 173 | 80.6 |
| 5 = 3 + 4 | S | 163 | 926 | 1550 | 928 | 554 |

| Clark County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 127 | 877 | 1240 | 862 | 348 |
| 2 | µLT | 19.3 | 232 | 406 | 242 | 73.1 |
| 3 = 1 + 2 | R | 146 | 1110 | 1640 | 1100 | 421 |
| 4 | E (week) | 19.3 | 232 | 406 | 242 | 73.1 |
| 5 = 3 + 4 | S | 166 | 1340 | 2050 | 1340 | 494 |

| Darke County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 126 | 827 | 962 | 635 | 406 |
| 2 | µLT | 16.9 | 199 | 333 | 170 | 70.7 |
| 3 = 1 + 2 | R | 143 | 1030 | 1290 | 805 | 477 |
| 4 | E (week) | 16.9 | 199 | 333 | 170 | 70.7 |
| 5 = 3 + 4 | S | 160 | 1220 | 1630 | 975 | 548 |

| Logan County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 277 | 712 | 1100 | 709 | 494 |
| 2 | µLT | 34.3 | 237 | 430 | 235 | 110 |
| 3 = 1 + 2 | R | 311 | 949 | 1530 | 944 | 604 |
| 4 | E (week) | 34.3 | 237 | 430 | 235 | 110 |
| 5 = 3 + 4 | S | 346 | 1190 | 1960 | 1180 | 714 |

| Mercer County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 97.4 | 621 | 720 | 474 | 413 |
| 2 | µLT | 11.6 | 148 | 252 | 135 | 86.1 |
| 3 = 1 + 2 | R | 109 | 769 | 971 | 609 | 499 |
| 4 | E (week) | 11.6 | 148 | 252 | 135 | 86.1 |
| 5 = 3 + 4 | S | 121 | 917 | 1220 | 744 | 586 |

| Miami County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 191 | 755 | 1040 | 639 | 383 |
| 2 | µLT | 22.6 | 199 | 395 | 163 | 76.1 |
| 3 = 1 + 2 | R | 214 | 954 | 1440 | 802 | 459 |
| 4 | E (week) | 22.6 | 199 | 395 | 163 | 76.1 |
| 5 = 3 + 4 | S | 236 | 1150 | 1830 | 965 | 535 |

| Montgomery County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 54 | 799 | 1380 | 571 | 235 |
| 2 | µLT | 5.91 | 173 | 377 | 110 | 41.8 |
| 3 = 1 + 2 | R | 60 | 971 | 1760 | 681 | 277 |
| 4 | E (week) | 5.91 | 173 | 377 | 110 | 41.8 |
| 5 = 3 + 4 | S | 65.9 | 1140 | 2140 | 791 | 319 |

| Shelby County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 128 | 594 | 591 | 540 | 295 |
| 2 | µLT | 16.3 | 165 | 235 | 143 | 61.1 |
| 3 = 1 + 2 | R | 144 | 760 | 827 | 682 | 356 |
| 4 | E (week) | 16.3 | 165 | 235 | 143 | 61.1 |
| 5 = 3 + 4 | S | 160 | 925 | 1060 | 825 | 418 |

# District 8

| Butler County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 135 | 841 | 994 | 886 | 266 |
| 2 | µLT | 10.1 | 210 | 381 | 147 | 46.2 |
| 3 = 1 + 2 | R | 145 | 1050 | 1370 | 1030 | 312 |
| 4 | E (week) | 10.1 | 210 | 381 | 147 | 46.2 |
| 5 = 3 + 4 | S | 155 | 1260 | 1760 | 1180 | 358 |

| Clermont County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 184 | 1830 | 1790 | 1390 | 493 |
| 2 | µLT | 15.4 | 469 | 693 | 262 | 92.2 |
| 3 = 1 + 2 | R | 199 | 2300 | 2490 | 1650 | 585 |
| 4 | E (week) | 15.4 | 469 | 693 | 262 | 92.2 |
| 5 = 3 + 4 | S | 215 | 2770 | 3180 | 1910 | 677 |

| Clinton County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 254 | 1390 | 1810 | 1360 | 455 |
| 2 | µLT | 27.4 | 393 | 735 | 320 | 105 |
| 3 = 1 + 2 | R | 281 | 1790 | 2550 | 1680 | 560 |
| 4 | E (week) | 27.4 | 393 | 735 | 320 | 105 |
| 5 = 3 + 4 | S | 308 | 2180 | 3280 | 2000 | 665 |

| Greene County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 195 | 1360 | 1780 | 1090 | 522 |
| 2 | µLT | 24.2 | 387 | 687 | 309 | 108 |
| 3 = 1 + 2 | R | 219 | 1750 | 2460 | 1390 | 629 |
| 4 | E (week) | 24.2 | 387 | 687 | 309 | 108 |
| 5 = 3 + 4 | S | 243 | 2140 | 3150 | 1700 | 737 |

| Hamilton County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 288 | 2510 | 2760 | 1650 | 768 |
| 2 | µLT | 21.9 | 627 | 1010 | 351 | 152 |
| 3 = 1 + 2 | R | 310 | 3140 | 3770 | 2000 | 920 |
| 4 | E (week) | 21.9 | 627 | 1010 | 351 | 152 |
| 5 = 3 + 4 | S | 332 | 3770 | 4780 | 2350 | 1070 |

| Preble County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 146 | 1470 | 1640 | 1320 | 582 |
| 2 | µLT | 18.7 | 360 | 625 | 335 | 120 |
| 3 = 1 + 2 | R | 165 | 1830 | 2270 | 1660 | 702 |
| 4 | E (week) | 18.7 | 360 | 625 | 335 | 120 |
| 5 = 3 + 4 | S | 184 | 2190 | 2890 | 1990 | 823 |

| Warren County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 147 | 1410 | 1460 | 1180 | 326 |
| 2 | µLT | 13.5 | 347 | 544 | 234 | 65.5 |
| 3 = 1 + 2 | R | 160 | 1750 | 2010 | 1420 | 391 |
| 4 | E (week) | 13.5 | 347 | 544 | 234 | 65.5 |
| 5 = 3 + 4 | S | 174 | 2100 | 2550 | 1650 | 457 |

## District 9

| Adams County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 132 | 799 | 1150 | 681 | 325 |
| 2 | µLT | 10.5 | 193 | 410 | 126 | 46.9 |
| 3 = 1 + 2 | R | 143 | 991 | 1560 | 807 | 372 |
| 4 | E (week) | 10.5 | 193 | 410 | 126 | 46.9 |
| 5 = 3 + 4 | S | 154 | 1180 | 1970 | 932 | 419 |

| Brown County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 187 | 818 | 1060 | 737 | 268 |
| 2 | µLT | 13.7 | 208 | 393 | 132 | 42.6 |
| 3 = 1 + 2 | R | 201 | 1030 | 1460 | 869 | 310 |
| 4 | E (week) | 13.7 | 208 | 393 | 132 | 42.6 |
| 5 = 3 + 4 | S | 215 | 1230 | 1850 | 1000 | 353 |

| Highland County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 100 | 658 | 1050 | 639 | 290 |
| 2 | µLT | 9.52 | 174 | 405 | 146 | 59.4 |
| 3 = 1 + 2 | R | 110 | 831 | 1460 | 785 | 350 |
| 4 | E (week) | 9.52 | 174 | 405 | 146 | 59.4 |
| 5 = 3 + 4 | S | 119 | 1010 | 1860 | 931 | 409 |

| Jackson County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 57.3 | 565 | 993 | 685 | 265 |
| 2 | µLT | 5.84 | 125 | 373 | 114 | 45.6 |
| 3 = 1 + 2 | R | 63.1 | 690 | 1370 | 799 | 311 |
| 4 | E (week) | 5.84 | 125 | 373 | 114 | 45.6 |
| 5 = 3 + 4 | S | 69 | 816 | 1740 | 913 | 356 |

| Lawrence County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 37.2 | 400 | 697 | 355 | 169 |
| 2 | µLT | 3.46 | 91.1 | 245 | 69.6 | 28.1 |
| 3 = 1 + 2 | R | 40.6 | 491 | 942 | 424 | 197 |
| 4 | E (week) | 3.46 | 91.1 | 245 | 69.6 | 28.1 |
| 5 = 3 + 4 | S | 44.1 | 582 | 1190 | 494 | 225 |

| Pike County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 52.6 | 497 | 738 | 635 | 172 |
| 2 | µLT | 4.39 | 115 | 271 | 99.8 | 26.6 |
| 3 = 1 + 2 | R | 57 | 611 | 1010 | 734 | 199 |
| 4 | E (week) | 4.39 | 115 | 271 | 99.8 | 26.6 |
| 5 = 3 + 4 | S | 61.4 | 726 | 1280 | 834 | 226 |

| Ross County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 93.8 | 891 | 1540 | 768 | 303 |
| 2 | µLT | 7.89 | 232 | 570 | 153 | 57.6 |
| 3 = 1 + 2 | R | 102 | 1120 | 2110 | 921 | 360 |
| 4 | E (week) | 7.89 | 232 | 570 | 153 | 57.6 |
| 5 = 3 + 4 | S | 110 | 1360 | 2680 | 1070 | 418 |

| Scioto County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 54.7 | 432 | 685 | 354 | 157 |
| 2 | µLT | 4.45 | 99.1 | 240 | 70.9 | 25.6 |
| 3 = 1 + 2 | R | 59.1 | 531 | 925 | 425 | 183 |
| 4 | E (week) | 4.45 | 99.1 | 240 | 70.9 | 25.6 |
| 5 = 3 + 4 | S | 63.6 | 630 | 1170 | 496 | 208 |

# District 10

| Athens County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 118 | 617 | 1070 | 635 | 347 |
| 2 | µLT | 12.1 | 150 | 441 | 145 | 57.3 |
| 3 = 1 + 2 | R | 131 | 767 | 1510 | 780 | 404 |
| 4 | E (week) | 12.1 | 150 | 441 | 145 | 57.3 |
| 5 = 3 + 4 | S | 143 | 918 | 1950 | 924 | 462 |

| Gallia County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 31.6 | 377 | 640 | 396 | 186 |
| 2 | µLT | 3.01 | 78.4 | 233 | 77.3 | 32.7 |
| 3 = 1 + 2 | R | 34.6 | 456 | 872 | 474 | 219 |
| 4 | E (week) | 3.01 | 78.4 | 233 | 77.3 | 32.7 |
| 5 = 3 + 4 | S | 37.6 | 534 | 1100 | 551 | 252 |

| Hocking County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 166 | 611 | 991 | 743 | 441 |
| 2 | µLT | 19.4 | 172 | 453 | 190 | 79.9 |
| 3 = 1 + 2 | R | 186 | 783 | 1440 | 933 | 521 |
| 4 | E (week) | 19.4 | 172 | 453 | 190 | 79.9 |
| 5 = 3 + 4 | S | 205 | 954 | 1900 | 1120 | 601 |

| Meigs County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 33.8 | 320 | 579 | 442 | 187 |
| 2 | µLT | 3.44 | 73.7 | 227 | 80.9 | 31.1 |
| 3 = 1 + 2 | R | 37.2 | 393 | 805 | 523 | 218 |
| 4 | E (week) | 3.44 | 73.7 | 227 | 80.9 | 31.1 |
| 5 = 3 + 4 | S | 40.7 | 467 | 1030 | 604 | 249 |

| Monroe County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 198 | 646 | 813 | 519 | 412 |
| 2 | µLT | 24.9 | 167 | 334 | 147 | 68.5 |
| 3 = 1 + 2 | R | 223 | 813 | 1150 | 666 | 481 |
| 4 | E (week) | 24.9 | 167 | 334 | 147 | 68.5 |
| 5 = 3 + 4 | S | 247 | 980 | 1480 | 814 | 549 |

| Morgan County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 180 | 630 | 962 | 654 | 340 |
| 2 | µLT | 20.1 | 146 | 420 | 153 | 52.6 |
| 3 = 1 + 2 | R | 200 | 776 | 1380 | 807 | 392 |
| 4 | E (week) | 20.1 | 146 | 420 | 153 | 52.6 |
| 5 = 3 + 4 | S | 220 | 922 | 1800 | 961 | 445 |

| Noble County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 183 | 703 | 1500 | 862 | 498 |
| 2 | µLT | 20.1 | 199 | 619 | 206 | 90.4 |
| 3 = 1 + 2 | R | 203 | 902 | 2120 | 1070 | 589 |
| 4 | E (week) | 20.1 | 199 | 619 | 206 | 90.4 |
| 5 = 3 + 4 | S | 223 | 1100 | 2730 | 1270 | 679 |

| Vinton County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 183 | 574 | 927 | 638 | 332 |
| 2 | µLT | 16.4 | 149 | 381 | 148 | 55 |
| 3 = 1 + 2 | R | 200 | 723 | 1310 | 786 | 387 |
| 4 | E (week) | 16.4 | 149 | 381 | 148 | 55 |
| 5 = 3 + 4 | S | 216 | 872 | 1690 | 934 | 442 |

| Washington County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 308 | 879 | 1670 | 965 | 641 |
| 2 | µLT | 31.9 | 236 | 756 | 220 | 110 |
| 3 = 1 + 2 | R | 340 | 1110 | 2430 | 1190 | 751 |
| 4 | E (week) | 31.9 | 236 | 756 | 220 | 110 |
| 5 = 3 + 4 | S | 372 | 1350 | 3180 | 1410 | 860 |

## District 11

| Belmont County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 640 | 1500 | 2200 | 1570 | 1030 |
| 2 | µLT | 64.3 | 447 | 961 | 394 | 188 |
| 3 = 1 + 2 | R | 704 | 1940 | 3160 | 1960 | 1210 |
| 4 | E (week) | 64.3 | 447 | 961 | 394 | 188 |
| 5 = 3 + 4 | S | 769 | 2390 | 4130 | 2360 | 1400 |

| Carroll County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 187 | 811 | 888 | 645 | 428 |
| 2 | µLT | 25.3 | 273 | 404 | 213 | 107 |
| 3 = 1 + 2 | R | 213 | 1080 | 1290 | 859 | 535 |
| 4 | E (week) | 25.3 | 273 | 404 | 213 | 107 |
| 5 = 3 + 4 | S | 238 | 1360 | 1700 | 1070 | 643 |

| Columbiana County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 520 | 1500 | 1690 | 1230 | 1280 |
| 2 | µLT | 80 | 544 | 823 | 431 | 307 |
| 3 = 1 + 2 | R | 600 | 2050 | 2510 | 1660 | 1580 |
| 4 | E (week) | 80 | 544 | 823 | 431 | 307 |
| 5 = 3 + 4 | S | 680 | 2590 | 3330 | 2090 | 1890 |

| Harrison County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 384 | 925 | 1240 | 739 | 620 |
| 2 | µLT | 45.6 | 316 | 536 | 227 | 127 |
| 3 = 1 + 2 | R | 429 | 1240 | 1780 | 966 | 747 |
| 4 | E (week) | 45.6 | 316 | 536 | 227 | 127 |
| 5 = 3 + 4 | S | 475 | 1560 | 2310 | 1190 | 873 |

| Holmes County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 253 | 929 | 1070 | 621 | 665 |
| 2 | µLT | 32.6 | 293 | 399 | 216 | 146 |
| 3 = 1 + 2 | R | 286 | 1220 | 1460 | 836 | 811 |
| 4 | E (week) | 32.6 | 293 | 399 | 216 | 146 |
| 5 = 3 + 4 | S | 319 | 1520 | 1860 | 1050 | 956 |

| Jefferson County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 454 | 1070 | 1510 | 1180 | 878 |
| 2 | µLT | 59.8 | 406 | 704 | 322 | 212 |
| 3 = 1 + 2 | R | 514 | 1470 | 2220 | 1500 | 1090 |
| 4 | E (week) | 59.8 | 406 | 704 | 322 | 212 |
| 5 = 3 + 4 | S | 573 | 1880 | 2920 | 1820 | 1300 |

| Tuscarwas County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 637 | 1400 | 1570 | 1090 | 879 |
| 2 | µLT | 78.6 | 512 | 807 | 395 | 221 |
| 3 = 1 + 2 | R | 716 | 1910 | 2380 | 1480 | 1100 |
| 4 | E (week) | 78.6 | 512 | 807 | 395 | 221 |
| 5 = 3 + 4 | S | 794 | 2430 | 3180 | 1880 | 1320 |

## District 12

| Cuyahoga County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 2760 | 7220 | 8290 | 4520 | 5160 |
| 2 | µLT | 395 | 2820 | 3520 | 1900 | 1580 |
| 3 = 1 + 2 | R | 3150 | 10000 | 11800 | 6420 | 6750 |
| 4 | E (week) | 395 | 2820 | 3520 | 1900 | 1580 |
| 5 = 3 + 4 | S | 3550 | 12900 | 15300 | 8330 | 8330 |

| Geauga County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 1100 | 3260 | 4110 | 2420 | 1920 |
| 2 | µLT | 211 | 1320 | 1990 | 1210 | 711 |
| 3 = 1 + 2 | R | 1310 | 4580 | 6100 | 3630 | 2630 |
| 4 | E (week) | 211 | 1320 | 1990 | 1210 | 711 |
| 5 = 3 + 4 | S | 1520 | 5900 | 8100 | 4840 | 3340 |

| Lake County | | | | | | |
|---|---|---|---|---|---|---|
| Months | | Nov | Dec | Jan | Feb | Mar |
| 1 | SS | 1380 | 2370 | 2950 | 1540 | 1450 |
| 2 | µLT | 179 | 912 | 1260 | 658 | 437 |
| 3 = 1 + 2 | R | 1560 | 3280 | 4220 | 2200 | 1890 |
| 4 | E (week) | 179 | 912 | 1260 | 658 | 437 |
| 5 = 3 + 4 | S | 1740 | 4190 | 5480 | 2860 | 2330 |

# Appendix 2: Simulation Results For Cuyahoga County

2005

| Policy | Ave. # of Stockouts | ± CI | Ave. Inventory level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amount Ordered | ± CI | Ave. # of Order Received | ± CI | Ave. Min. Inventory |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual | 0 | 0 | 12900 | - | - | - | 860 | - | 46 | - | |
| 1 | 0 | 0 | 12500 | 123 | 12.7 | 0.31 | 850 | 34.7 | 49.5 | 2.32 | 11200 |
| 2 | 1.6 | 2.88 | 7320 | 282 | 15.5 | 0.44 | 855 | 37.5 | 69.3 | 3.91 | 4120 |
| 3 | 0 | 0 | 9810 | 187 | 15.3 | 0.26 | 836 | 35.1 | 59.8 | 2.74 | 7800 |
| 4 | 0 | 0 | 10700 | 119 | 14.7 | 0.28 | 831 | 31.4 | 56.9 | 2.3 | 9710 |
| 5 | 0 | 0 | 8610 | 168 | 16 | 0.33 | 843 | 33.7 | 64.5 | 2.81 | 7510 |
| 6 | 0.133 | 0.27 | 7740 | 248 | 17 | 0.29 | 842 | 34.7 | 70 | 3.29 | 5110 |
| 7 | 0 | 0 | 9680 | 222 | 15.8 | 0.38 | 842 | 34.6 | 59.2 | 2.76 | 7566 |
| 8 | 0 | 0 | 10500 | 184 | 15.3 | 0.42 | 835 | 35.3 | 56.6 | 2.49 | 8880 |
| 9 | 0.133 | 0.27 | 8730 | 234 | 17.3 | 0.28 | 833 | 31.8 | 65.1 | 2.81 | 6270 |
| 10 | 0.133 | 0.27 | 8043 | 202 | 16.6 | 0.27 | 848 | 33.9 | 69.5 | 3 | 6070 |
| 11 | 0 | 0 | 9830 | 176 | 15.4 | 0.25 | 844 | 34.5 | 59.1 | 2.72 | 9830 |
| 12 | 0 | 0 | 10700 | 133 | 14.7 | 0.33 | 837 | 32.7 | 56.4 | 2.29 | 9600 |
| 13 | 0.133 | 0.27 | 9030 | 189 | 16.7 | 0.3 | 839 | 31.2 | 64.7 | 2.6 | 7220 |

2004

| Policy | Ave. # of Stockouts | ± CI | Ave. Inventory level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amount Ordered | ± CI | Ave. # of Order Received | ± CI | Ave. Min. Inventory |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual | 0 | - | 21000 | - | - | - | 937 | - | 40 | - | - |
| 1 | 0 | 0 | 15700 | 216 | 9.2 | 0.33 | 854 | 54.7 | 35.5 | 2.14 | 14400 |
| 2 | 0 | 0 | 7300 | 190 | 16.3 | 0.5 | 838 | 34.6 | 67.1 | 3.09 | 6050 |
| 3 | 0.167 | 0.34 | 9690 | 161 | 14.6 | 0.38 | 826 | 31.7 | 56.7 | 2.35 | 8410 |
| 4 | 0.167 | 0.28 | 10300 | 179 | 13.8 | 0.34 | 832 | 31.8 | 53.5 | 2.11 | 9500 |
| 5 | 0.1 | 0.2 | 8520 | 177 | 14.8 | 0.28 | 839 | 35.6 | 61.5 | 2.83 | 7140 |
| 6 | 0 | 0 | 7340 | 141 | 17 | 0.52 | 845 | 34.2 | 66.2 | 2.9 | 6140 |
| 7 | 0.1 | 0.2 | 9220 | 95 | 16 | 0.4 | 825 | 31.2 | 56.7 | 2.3 | 8350 |
| 8 | 0.133 | 0.27 | 9870 | 90.9 | 15.3 | 0.28 | 826 | 35.6 | 54 | 2.55 | 9200 |
| 9 | 0 | 0 | 8410 | 67.9 | 17.4 | 0.3 | 833 | 32.9 | 61.8 | 2.63 | 7880 |
| 10 | 0 | 0 | 7900 | 183 | 15.2 | 0.5 | 854 | 36.2 | 65.9 | 3.17 | 6630 |
| 11 | 0.1 | 0.2 | 9900 | 193 | 14.1 | 0.27 | 827 | 34.4 | 57 | 2.63 | 8610 |
| 12 | 0.133 | 0.27 | 10400 | 190 | 13.5 | 0.27 | 831 | 37.2 | 53.5 | 2.47 | 9210 |
| 13 | 0 | 0 | 8930 | 168 | 15.4 | 0.36 | 850 | 34.6 | 60.6 | 2.72 | 8100 |

2003

| Policy | Ave. # of Stockouts | ± CI | Ave. Inventory level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amount Ordered | ± CI | Ave. # of Order Received | ± CI | Ave. Min. Inventory |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual | 0 | - | 15900 | - | - | - | 796 | - | 57 | - | - |
| 1 | 0 | 0 | 12400 | 115 | 13 | 0.32 | 823 | 35.3 | 48.1 | 2.31 | 11300 |
| 2 | 0 | 0 | 7050 | 144 | 21.7 | 0.37 | 812 | 29.4 | 72.5 | 2.8 | 6000 |
| 3 | 0 | 0 | 9250 | 162 | 15.5 | 0.41 | 834 | 32.8 | 59.8 | 2.65 | 7500 |
| 4 | 0 | 0 | 9900 | 117 | 15.7 | 0.22 | 824 | 34.4 | 57.3 | 2.56 | 9070 |
| 5 | 0 | 0 | 8030 | 173 | 15.1 | 0.4 | 849 | 33.2 | 64.2 | 2.88 | 6260 |
| 6 | 0 | 0 | 7060 | 195 | 17.9 | 0.48 | 839 | 34.9 | 70.3 | 3.15 | 4825 |
| 7 | 0 | 0 | 9000 | 104 | 16.6 | 0.35 | 832 | 35.2 | 59.9 | 2.77 | 8090 |
| 8 | 0 | 0 | 9660 | 63.9 | 16.9 | 0.32 | 825 | 30.8 | 57.1 | 2.38 | 9960 |
| 9 | 0 | 0 | 8150 | 129 | 17.5 | 0.27 | 837 | 32.9 | 64.8 | 2.89 | 7048 |
| 10 | 0 | 0 | 7490 | 251 | 16.5 | 0.66 | 852 | 37.1 | 69.6 | 3.51 | 4470 |
| 11 | 0 | 0 | 9430 | 133 | 15.5 | 0.24 | 838 | 35.7 | 59.7 | 2.83 | 8180 |
| 12 | 0 | 0 | 10100 | 96.6 | 15.7 | 0.19 | 833 | 31.9 | 56.8 | 2.31 | 9360 |
| 13 | 0 | 0 | 8530 | 165 | 16.3 | 0.37 | 851 | 34.2 | 64.1 | 2.93 | 7140 |

2002

| Policy | Ave. # of Stockouts | ± CI | Ave. Inventory level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amount Ordered | ± CI | Ave. # of Order Received | ± CI | Ave. Min. Inventory |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual | 0 | - | 21200 | - | - | - | 603 | - | 39 | - | - |
| 1 | 0 | 0 | 12700 | 16.1 | 7.2 | 0.14 | 826 | 51.3 | 18.5 | 1.08 | 12500 |
| 2 | 0 | 0 | 8110 | 49.7 | 9.67 | 0.18 | 851 | 52 | 33.8 | 2.3 | 7760 |
| 3 | 0 | 0 | 10300 | 30 | 8.8 | 0.15 | 808 | 40.9 | 24.2 | 1.35 | 10200 |
| 4 | 0 | 0 | 11400 | 17.8 | 7.67 | 0.18 | 821 | 48.2 | 20.7 | 1.17 | 11200 |
| 5 | 0 | 0 | 9280 | 20 | 9.67 | 0.18 | 819 | 41 | 29.2 | 1.64 | 9200 |
| 6 | 0 | 0 | 8840 | 54.3 | 9.7 | 0.17 | 859 | 54.6 | 33.5 | 2.25 | 8450 |
| 7 | 0 | 0 | 10600 | 21.8 | 8.9 | 0.11 | 808 | 42.7 | 24.1 | 1.3 | 10400 |
| 8 | 0 | 0 | 11400 | 17 | 8.1 | 0.13 | 803 | 47.7 | 21.4 | 1.22 | 11200 |
| 9 | 0 | 0 | 9800 | 24.3 | 9.7 | 0.17 | 827 | 43.4 | 28.9 | 1.58 | 9800 |
| 10 | 0 | 0 | 8820 | 56.2 | 9.2 | 0.15 | 870 | 55.9 | 33.5 | 2.29 | 8390 |
| 11 | 0 | 0 | 10600 | 19.3 | 8.17 | 0.14 | 825 | 43.3 | 23.9 | 1.37 | 10400 |
| 12 | 0 | 0 | 11400 | 17.8 | 7.67 | 0.18 | 821 | 48.2 | 20.7 | 1.17 | 11200 |
| 13 | 0 | 0 | 9790 | 26.3 | 9.2 | 0.15 | 841 | 46.4 | 28.9 | 1.63 | 9540 |

2001

| Policy | Ave. # of Stockouts | ± CI | Ave. Inventory level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amount Ordered | ± CI | Ave. # of Order Received | ± CI | Ave. Min. Inventory |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual | 0 | - | 12400 | - | - | - | 704 | - | 59 | - | - |
| 1 | 0 | 0 | 10500 | 148 | 12.4 | 0.3 | 839 | 36.9 | 46.2 | 2.11 | 9490 |
| 2 | 1.83 | 1.23 | 7340 | 327 | 17.7 | 0.58 | 796 | 37.2 | 64.6 | 3.05 | 4810 |
| 3 | 0 | 0 | 9700 | 194 | 12.4 | 0.33 | 838 | 38.8 | 50.4 | 2.63 | 7630 |
| 4 | 0 | 0 | 10400 | 164 | 12.8 | 0.32 | 823 | 38.1 | 48.1 | 2.57 | 8580 |
| 5 | 0.967 | 1.44 | 8260 | 312 | 12.9 | 0.39 | 838 | 38.5 | 55.8 | 3.02 | 5300 |
| 6 | 1.73 | 1.24 | 7640 | 272 | 17.5 | 0.6 | 813 | 37.2 | 63 | 3.05 | 5160 |
| 7 | 0.033 | 0.07 | 9530 | 184 | 12.7 | 0.32 | 832 | 38.3 | 50.7 | 2.83 | 7790 |
| 8 | 0 | 0 | 10000 | 154 | 12.7 | 0.32 | 824 | 37 | 48 | 2.56 | 8490 |
| 9 | 0.267 | 0.48 | 8440 | 287 | 12.3 | 0.52 | 849 | 42.3 | 55.3 | 3.21 | 5160 |
| 10 | 1.73 | 1.24 | 8130 | 316 | 17.1 | 0.56 | 815 | 36 | 63.1 | 2.98 | 5920 |
| 11 | 0.033 | 0.07 | 10000 | 211 | 12.3 | 0.26 | 841 | 40.4 | 50.4 | 2.93 | 7790 |
| 12 | 0 | 0 | 10400 | 205 | 12.4 | 0.3 | 831 | 37.8 | 47.7 | 2.59 | 8490 |
| 13 | 0.267 | 0.48 | 9000 | 283 | 11.8 | 0.51 | 858 | 45.1 | 55 | 3.54 | 10100 |

2000

| Policy | Ave. # of Stockouts | ± CI | Ave. Inventory level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amount Ordered | ± CI | Ave. # of Order Received | ± CI | Ave. Min. Inventory |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual | 0 | - | 13100 | - | - | - | 781 | - | 37 | - | - |
| 1 | 0 | 0 | 11900 | 65.7 | 8.1 | 0.18 | 848 | 49.4 | 28.7 | 1.78 | 11500 |
| 2 | 0 | 0 | 7810 | 94.3 | 11.2 | 0.18 | 855 | 42.4 | 45.3 | 2.35 | 7000 |
| 3 | 0 | 0 | 9960 | 90.4 | 9.23 | 0.16 | 846 | 48.1 | 35.1 | 2.16 | 9240 |
| 4 | 0 | 0 | 10800 | 55 | 9.1 | 0.23 | 838 | 47.6 | 32.4 | 2.03 | 10500 |
| 5 | 0 | 0 | 9030 | 57.8 | 10.1 | 0.23 | 854 | 44.1 | 40 | 2.14 | 8540 |
| 6 | 0 | 0 | 8140 | 80.3 | 11.6 | 0.18 | 846 | 42.6 | 46 | 2.61 | 7540 |
| 7 | 0 | 0 | 9870 | 60.6 | 10.6 | 0.19 | 833 | 42.3 | 35.6 | 1.87 | 9370 |
| 8 | 0 | 0 | 10800 | 50.6 | 9.77 | 0.16 | 834 | 47.3 | 32.6 | 1.83 | 10500 |
| 9 | 0 | 0 | 9110 | 53.4 | 11.6 | 0.18 | 825 | 36 | 41.4 | 2.04 | 8710 |
| 10 | 0 | 0 | 8350 | 84.7 | 10.1 | 0.25 | 872 | 49.1 | 44.6 | 2.69 | 7930 |
| 11 | 0 | 0 | 10100 | 96 | 9.2 | 0.16 | 852 | 48.1 | 34.9 | 2.19 | 9310 |
| 12 | 0 | 0 | 11100 | 91.8 | 8.3 | 0.17 | 860 | 50.5 | 31.5 | 1.98 | 10500 |
| 13 | 0 | 0 | 9330 | 66.3 | 10.1 | 0.25 | 853 | 43.3 | 40 | 2.16 | 8840 |

1999

| Policy | Ave. # of Stockouts | ± CI | Ave. Inventory level | ± CI | Ave. # of Orders Placed | ± CI | Ave. Amount Ordered | ± CI | Ave. # of Order Received | ± CI | Ave. Min. Inventory |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual | 0 | - | 14100 | - | - | - | 691 | - | 45 | - | - |
| 1 | 0.1 | 0.15 | 13300 | 162 | 8.3 | 0.17 | 861 | 55.1 | 33.3 | 2.15 | 12100 |
| 2 | 0.667 | 0.71 | 8140 | 197 | 11.2 | 0.2 | 874 | 44.2 | 51.4 | 2.8 | 6590 |
| 3 | 0.733 | 0.84 | 10200 | 192 | 10.1 | 0.18 | 865 | 46.4 | 41.1 | 2.46 | 8540 |
| 4 | 1.2 | 0.99 | 11100 | 217 | 9.5 | 0.21 | 853 | 46.6 | 38.8 | 2.26 | 9440 |
| 5 | 0.667 | 0.71 | 9310 | 185 | 11.2 | 0.2 | 859 | 39.2 | 46.7 | 2.34 | 9310 |
| 6 | 0.567 | 0.59 | 8470 | 200 | 11 | 0.27 | 874 | 44 | 51.4 | 2.83 | 7120 |
| 7 | 0.533 | 0.7 | 10200 | 185 | 9.87 | 0.29 | 881 | 54.9 | 40.8 | 2.66 | 8750 |
| 8 | 1.1 | 0.77 | 11100 | 209 | 9.13 | 0.21 | 863 | 55.8 | 38.7 | 2.52 | 9570 |
| 9 | 0.567 | 0.59 | 9430 | 194 | 11 | 0.27 | 859 | 39.2 | 46.8 | 2.32 | 8270 |
| 10 | 0.567 | 0.59 | 8550 | 185 | 10.9 | 0.25 | 874 | 44.1 | 51.3 | 2.83 | 7120 |
| 11 | 0.533 | 0.7 | 10200 | 182 | 9.8 | 0.28 | 883 | 54.6 | 40.7 | 2.66 | 8750 |
| 12 | 1.1 | 0.77 | 11200 | 205 | 9.1 | 0.21 | 864 | 55.7 | 38.7 | 2.52 | 9570 |
| 13 | 0.567 | 0.59 | 9520 | 176 | 10.9 | 0.25 | 859 | 39.3 | 46.7 | 2.31 | 8270 |