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End users/uses of precipitation forecasts

Understanding user decision making and value of improved precipitation forecasts: Lessons from a case study

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1. Introduction

This paper describes the requirements for understanding the decision processes of users of weather information, and illustrates those requirements with a case study involving surface transportation in the Northeastern U.S. We also describe the elements of a credible estimate of the value of an improved forecast, and our unsuccessful attempt to satisfy them. We argue that, for many important uses of weather information, the data related to both use of meteorological information *and* basic meteorological information itself that are required for credible estimates of forecast value are not available and that systematic, long term data collection efforts will be required to support future studies of forecast use and value.

2. Why study the use of weather forecasts?

Scientific research on atmospheric processes and weather forecasting offers the potential for improvements in weather forecasts (such as QPF), as measured by scientific criteria. Furthermore, such improvements have the *potential* for avoiding injury and death, averting property and environmental damage, and other societal benefits. Although the potential societal value related to improved weather forecasts is substantial, the realization of that potential is not automatic. The scientific community has a responsibility to work toward that realization.

The success of that work depends on a number of factors. Obtaining the actual (not just the potential) value of improved forecast technology requires a) a forecasting process that translates improved science and technology into improved forecast products that are targeted to user needs, b) a communication process that effectively delivers forecast information to users in a timely fashion and in a form useful for making weather-information-sensitive decisions, c) users who incorporate the forecast product into their decisions in order to make better choices among available alternatives (see Glantz & Tarleton, 1991).

Meeting these requirements begins with the detailed understanding of user needs and user decision processes that is the outcome of systematic study. Such study also provides a foundation for studies of the value of current forecasts and forecast improvement.

3. Snow removal case study

We conducted an exploratory case study of the use of weather information for decision making and the economic value of improved quantitative precipitation forecasts for a surface transportation activity in the northeastern U.S. The study was exploratory because it focused on use and value of actual and potential forecast products, a largely neglected area of scholarship. Thus, lessons learned from the methodology, data collection, and analysis for the conduct of future studies of weather forecast use and value are considered to be as, if not more, important than the details of the case study itself.

We chose to study snow removal on the New York Thruway. Snow removal is an important activity for thousands of miles of highway that is subject to winter weather. The snow removal budget for the New York Thruway alone is approximately $10 million/year. The benefit to travelers in safety and convenience and the environmental costs due to the use of salt on the roadways (e.g., McKeever, *et al.*, 1998; Vitaliano, 1992) may be many times that amount.

An understanding of the decisions involved in snow removal was gained through interviews, observations, and other sources. Data for modeling the effect of improved QPF on the decision process and estimating the value of an improved forecast were sought from a number of sources.

3.1 Interviews

Snow removal is the responsibility of the 23 Thruway Section Maintenance Facilities that are distributed along the 496-mile Thruway. Interviews were conducted at five of 23 Facilities during November, 1998. The five facilities were chosen to represent the various weather and traffic conditions that occur along the Thruway. The facilities chosen (with mile markers, measured from New York City) were:

Buffalo (mile 423.19) – Urban, substantial snow, much of it from lake-effect processes.

West Henrietta (mile 362.44) – A major exit for Rochester.

Verona (mile 252.71) – Mostly rural, snowiest station on the Thruway.

Albany (mile 141.92) – Urban, beyond most lake-effect snow.

Harriman (mile 45.20) – North of New York City – Heavy traffic at times, less snow.

Interviews lasted 1-2 hours and were recorded and transcribed. Interviewees were the Supervisor I’s (the head supervisor) and, in the case of Buffalo and Albany, Supervisor II’s also participated. These supervisors have the responsibility for snow removal actions taken before, during, and after a storm. Information obtained from the interviews included: steps taken to prepare for the snow season, responsibility and authority for the decision to send out trucks, choices available when snow is threatening, sources of weather information, required lead times for action, timeliness and accuracy of feedback about results, types of errors made, rewards and incentives, and desired weather information.

We also interviewed the Albany Division Engineer who oversees maintenance for all facilities in his division. (The Thruway is divided into four divisions.)

3.2 Observations

Observations were made of snow-fighting operations at the Albany maintenance facility during the March 14-15, 1999, storm. Weather reports from a network of trained spotters maintained by John Quinlan were also obtained, as were the reports from drivers' in several sections of the Thruway of their activity during this storm.

3.3 Other information

We also examined the "logs" (i.e., journals recording driver activity) that drivers keep during snow removal operations and reviewed maintenance manuals and other documents related to winter highway maintenance. The staff at the maintenance facilities and the Thruway headquarters in Albany were cooperative and supportive of our study.

3.4 Data on forecast quality and costs

The following types of data were obtained from various sources:

- Thruway data on costs and operations
- National accident data
- Toll barrier weather observations
- RUC model runs (Nov. 1998 - March 1999)
- NWS storm data for New York
- NY climatological snowfall data from NOAA

4. Results—the decision making process

Describing the decision making process requires, at a minimum, describing the key decision makers, their goals and the context in which they operate, the information they use to make decisions, the alternative actions available to them, and the important decision points. These requirements are illustrated below for our case study.

4.1 Key decision makers

The key decision makers in the process, and their respective roles are described below.

4.1.1 Supervisors

Each Thruway Maintenance Office has three supervisors who cover the three shifts each day. Supervisors are responsible for a section of the Thruway (usually about 30 miles). They call in extra staff if needed and decide when and where to send out trucks to plow and salt.

4.1.2 Drivers

Drivers are responsible for a specific route. They make observations and can make some independent decisions about when to plow and apply salt. Obviously, they do not plow if they do not see snow on the roadway. More experienced drivers are given greater freedom to decide how to treat their route. Drivers are in radio contact with supervisors and report weather conditions regularly.

4.1.3 System division engineer (post-event review)

Each of the four Thruway Division engineers is responsible for several maintenance offices. Generally, they do not get involved in decisions about specific storms. After the storm has ended, they review the outcomes of each storm and can influence the supervisors' actions in subsequent storms.

4.1.4 Thruway headquarters staff

Staff at Thruway headquarters in Albany makes policy, determines the maintenance budget, approves equipment purchases, and makes other decisions that affect snowfighting capability in the long run.

We chose to focus exclusively on the Thruway maintenance supervisors. They have the decision making responsibility for each storm, and their judgments and decisions are directly affected by weather forecasts.

4.2 Goals and decision context

Understanding a decision process requires an understanding of the decision makers' goals and the context in which they operate. In other words, we must first address the question "What are the decision makers trying to accomplish, and what are the opportunities and constraints that they have to cope with in order to achieve this goal?" Based on our interviews and observations, we conclude that the following are the key elements of snowfighting:

- The primary goal of snowfighting is to serve public safety and convenience by keeping the maximum possible traction on the roadway.
- Supervisors want to be proactive. They try to have trucks loaded and on the road before precipitation starts.
- The purpose of snowfighting is to keep the roadway clear by plowing and keeping the freezing temperature of the pavement below the pavement temperature by applying salt.
- If there is rain or snow present, salt must be applied (if possible) before the pavement temperature drops below the freezing temperature. This means, in effect, that the supervisor must implicitly predict pavement temperature.
- Due to uncertainty about the weather, some errors are inevitable. The imperfect link between air temperature and pavement temperature adds to the uncertainty.

Table 1 is a highly simplified illustration of the different kinds of error that maintenance supervisors must consider in making decisions.

Table 1. Simplified decision table describing the errors that decision makers must consider.

		Decision: Don't send trucks	Decision: Send trucks
Event	Snow	Error (Type b) Costs: Risk of accidents and inconvenience	Good decision Benefits: Public safety and convenience Costs: Payroll, fuel, maintenance, salt
	No snow	Good decision Roads are safe No costs	Error (Type a) Costs: Payroll, fuel, maintenance, salt

There are two possible types of errors represented in Table 1— (a) sending out trucks too soon or when it is not necessary or applying too much salt and (b) not sending trucks, sending too few trucks, sending trucks too late, or not applying enough salt when it is necessary. In this snowfighting context, decision makers considered the second error much more serious than the first. Unfortunately, there is no data on which kind of error is more common, but it seems likely that it is Type a.

Supervisors cope with the unavoidable uncertainty in their job by being risk averse. They want to avoid Type b errors if at all possible. Their snow removal budget, and the incentives and culture of the Thruway encourage them to use salt and trucks and personnel liberally in order to avoid this type of error. This does not mean that they are not concerned about saving money and salt. Given the inherent uncertainty that they have to deal with, it is better to risk several Type a errors than to experience one Type b error. As a result, the best opportunity to benefit from an improved weather forecast would be in the reductions of errors of Type a. In other words, there will be an economic benefit to improved forecasts if they result in savings associated with staffing, fuel, maintenance, and salt without sacrificing public safety or convenience.

4.3 Information used for decision making

Studies of the use and value of weather forecasts must recognize that decisions are rarely based on weather information alone (Stewart, Katz, and Murphy, 1984, Stewart, 1997). They must also recognize that weather forecasts are often not the decision makers' only source of weather information. Furthermore, weather information is typically embedded in a matrix of other relevant information that the decision maker must consider.

Since Thruway supervisors are faced with decisions that involve uncertainty about the weather and their decisions can have serious consequences, they constantly seek weather information. They are aware of local weather conditions and forecasts during the snow season. As snow approaches, they use NWS zone forecasts, DTN Corporation radar displays and other information, contacts with other Thruway facilities, and personal observation to make decisions. Based on our interviews, it is clear that supervisors obtain weather information from a variety of sources, but they still want better, locally specific, forecasts of storm onset, storm intensity, and storm duration.

At the time of our study, the DTN displays had been installed in each maintenance office for less than a year. The supervisors expressed enthusiasm for this system. The display they used most (in the case of some supervisors, the only display they used) was the Northeast regional radar (covering the Northeastern U.S.). Most supervisors felt that they could use this display to make their own forecasts that were more specific and timely than the forecasts that had been previously provided by a private weather forecasting firm. Their preference for the radar display, even though they are not trained in the subtleties of interpreting radar, is evidence of their desire for more specific local information than is generally provided by forecasters.

In addition to weather information, supervisors must consider the time of day and week that the storm occurs. Snow occurring during rush hour may require special attention due to heavy traffic that both exposes more motorists to risk and can inhibit the movement of the trucks. Snow occurring on weekends may require more lead time to call in extra drivers because weekend maintenance crews are generally smaller. In general, the supervisors must take into account the number of trucks and drivers that are available, as well as other local road conditions, such as bridges and overpasses that may need early and repeated treatment.

To summarize, the sources of weather information used in snowfighting decision making include:

- Forecast (NWS zone forecast)
- DTN radar display
- Reports from other Thruway facilities (hourly roll-call, includes pavement temperature)
- Observation
  - ✓ patrolling with pavement temperature sensors
  - ✓ observations at maintenance office
  - ✓ reports from drivers
- Time of day/week/season
- Location on Thruway
- Information about available materials, labor, equipment

4.4 Overview of decision process

Snow plowing involves a dynamic decision process as illustrated, schematically, and in a simplified form, in Figure 1. The decision to devote resources to snowfighting, (represented in the figure by the decision to send out all trucks, some trucks, or no trucks) and the level of those resources is made continuously in the period preceding and during the storm. The outcomes of decisions made at one time will depend on weather events (represented in the figure as snow and no snow), and will affect decisions made at future times.

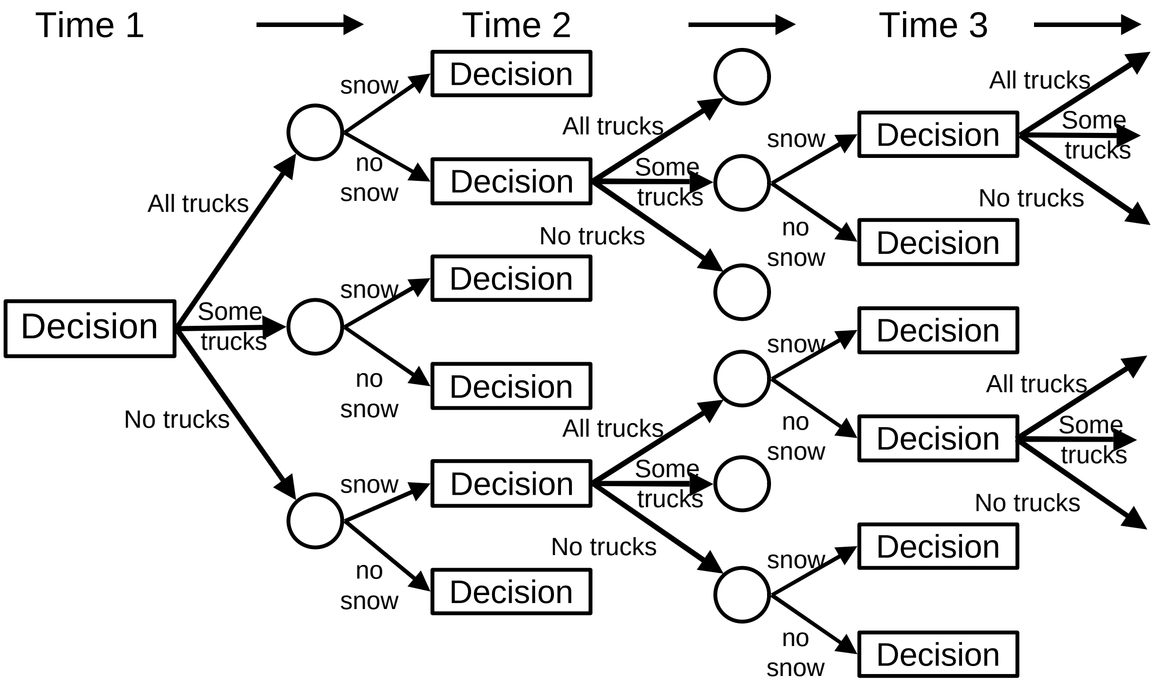

Figure 1. Schematic description of dynamic snowfighting decision process.

Understanding the supervisors' decision process involves understanding what alternatives they have available, the multiple decision points in the process, and the information that they use in making decisions at each point in the process. These are described in the following sections.

4.5 Alternative actions

Dealing with snow on the Thruway begins with pre-season preparation, e.g., setting up trucks with spreaders, plows, and wings, and training drivers. These activities are important, but not sensitive to weather forecasts.

Action for a specific weather event is triggered by a forecast of both cold weather and precipitation (risk of snow or ice on roadway). This usually occurs a few days in advance of the storm and the information may come from a commercial radio or TV broadcast, the DTN terminal, or other means of communication. The supervisors constantly monitor weather information.

The alternative actions that the supervisor must consider will vary as the storm progresses.

- When snow is anticipated, the supervisor may need to call in extra drivers. He must decide when to do so and how many to call.
- Before plowing has started, the supervisor must consider a number of decision alternatives:
  - ✓ Do nothing
  - ✓ Send a reduced number of trucks
  - ✓ Send out all trucks
- After plowing has started, alternatives are

- ✓ Keep trucks out
- ✓ Recall some trucks (or keep them in when they come in to refill)
- ✓ Recall all trucks

- During plowing and salting, it is possible to modify the route and the amount of salt applied.

4.6 Decision points

Figure 2 describes the decision points as a storm progresses. Although they are listed in a roughly chronological order, the decision process is dynamic and iterative, as described above.

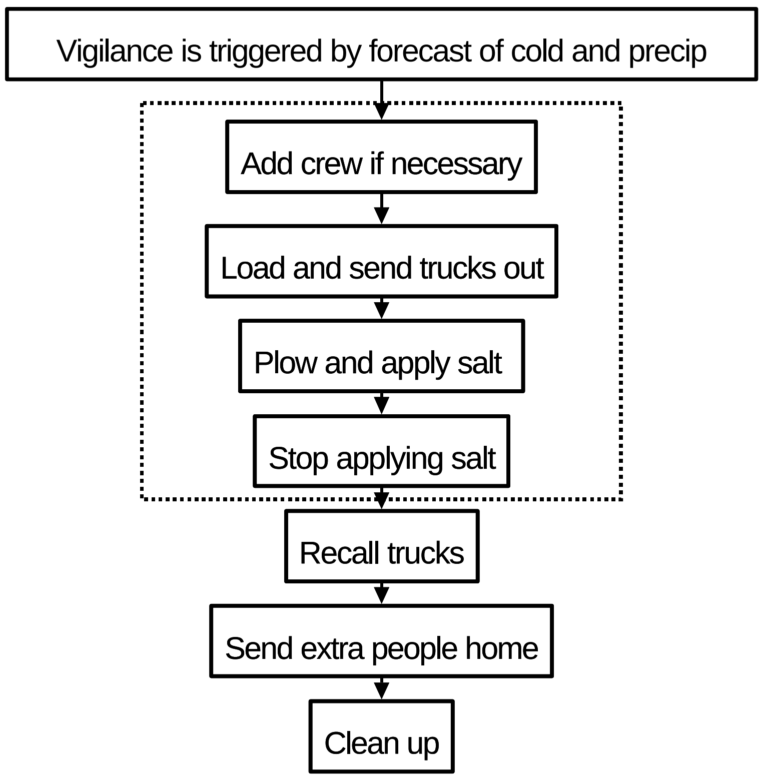

Figure 2. Critical decision points in the decision process for a specific weather event.

The information used, actions, lead time, and costs and benefits associated with each step in Figure 2 are described below.

4.6.1 Vigilance

- Information: Forecast (NWS zone forecast), observations, DTN radar displays.
- Actions: Check equipment, including lights, oil, fuel, brakes, plows, cutting edges, etc.
- Lead time: Up to 8 hours
- Costs and benefits: No additional costs, but people may be diverted from other jobs.

4.6.2 Add crew if necessary

- Information: Forecast (NWS zone forecast), DTN radar display, reports from other Thruway facilities (hourly roll-call), observation
- Actions: Take crews off other tasks, call in extra crew, occasionally trucks can be called in from neighboring sections. Actions are constrained by union requirement of a minimum 4 hour shift for crew that is called in. A minimum 2-week notice is required to change someone's shift without having to pay them extra, virtually eliminating the possibility that shifts can be rearranged to accommodate a storm.
- Lead time: 30-120 minutes, depending on where people have to travel from
- Costs and benefits: Payroll, overtime

4.6.3 Load and send trucks out

- Information: Observation by supervisor, DTN radar display, forecast
- Actions: Load trucks with salt, dispatch to pre-assigned route, stand-by if necessary
- Lead time: To load – 15 min; to reach route – 0 to 30 min
- Costs and benefits: Fuel and maintenance

4.6.4 Plow and apply salt (or other material)

- Information: Observation by drivers and supervisors on patrol (Some supervisors have pavement temperature sensors.), DTN radar display
- Actions: Set rate of salt application, change rate of application during storm, pre-wet salt, use magic, zero velocity spreaders
- Lead time: 0
- Costs and benefits: Salt and Fuel and Maintenance, vehicle corrosion ($113/ton), highway structure corrosion ($615/ton for bridge repairs), aesthetics ($75/ton for tree damage in Adirondack park region), health damage from sodium in drinking water (speculative) (estimates from Vitaliano, 1992)

Note: Road closure is a possible action that is very rare on the Thruway and is a decision made in a separate decision process by the State Police, usually for visibility reasons.

4.6.5 Stop applying salt

- Information: Observation by drivers/supervisor, DTN radar display
- Actions: Stop spreading
- Lead Time: 0
- Costs and benefits: Salt savings

4.6.6 Recall trucks

- Information: Observation by drivers/supervisor, DTN radar display
- Actions: Recall trucks to maintenance office
- Lead time 0
- Costs and benefits: Fuel and maintenance

4.6.7 Send extra people home

- Information: Observation by drivers/supervisor
- Actions: Send people home, assign them to other jobs
- Lead time: 0
- Costs and benefits: Potential savings?

4.6.8 Clean up

- Information: Observation of snow on Thruway
- Actions: Empty spreaders, plow shoulders, median, etc.
- Lead time: 0
- Costs and benefits: Payroll, fuel, maintenance

4.6.9 Summary

The decision points that are most sensitive to weather information are those enclosed in the box in Figure 2: Add crew, load and send trucks out, plow and apply salt, and stop applying salt. Benefits of improved forecasts are likely to be obtained by influencing these decisions.

Figure 3 places the supervisors' decision process in the context of weather information and situational variables. We assume that improved QPF would affect the decision process through improved NWS forecasts or by being incorporated into a weather information system such as the DTN system. It is also possible that improved QPF might have a direct effect on the decision process. What is clear from Figure 3 is that any evaluation of improved QPF must be done in the context both of other information that is available to the decision maker and of the situational factors (e.g., time and location of storm) that affect their decisions.

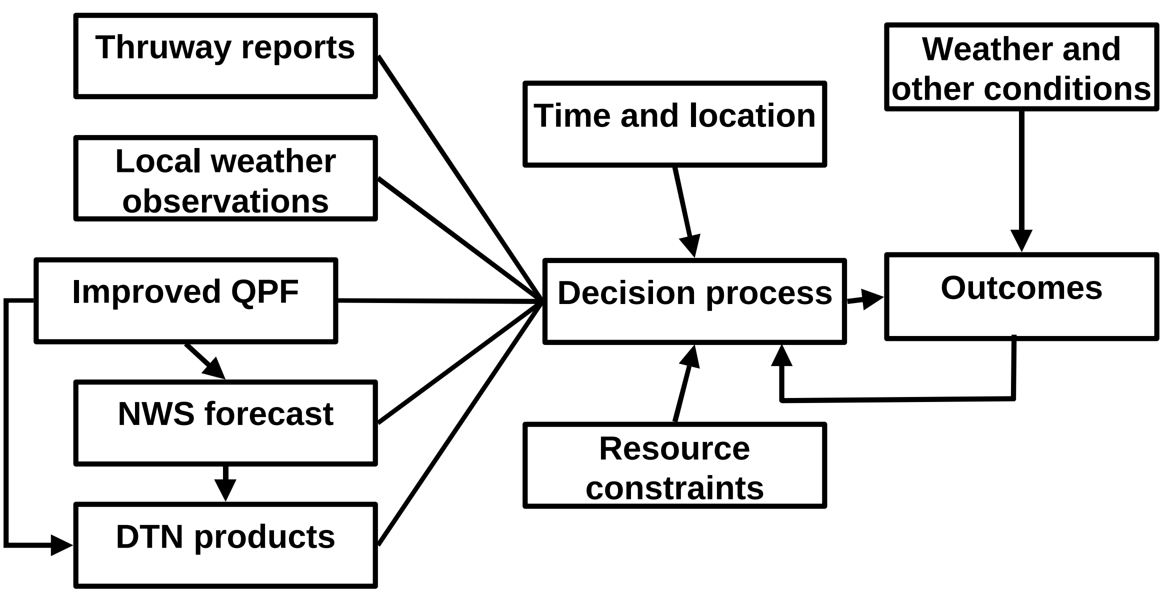

Figure 3. Overview of weather information and situational variables that affect snowfighting decisions making and role of improved QPF.

4.7 Summary of the decision process

The following major conclusions can be drawn:

- The decision process is inherently dynamic. Facility supervisors make a stream of decisions before, during, and after a winter storm.
- The supervisors operate in an environment that provides good feedback about the results of their actions, so they have an opportunity to learn with experience.
- Thruway supervisors tend to operate intuitively rather than analytically (Hammond, 1996). As a result, they cannot always describe in precise detail their rules for initiating action when snow threatens. Modeling their decision processer requires observations and experiments. Interviews alone will not suffice.
- Although supervisors are not sophisticated with regard to weather forecasting, they are experienced, vigilant, risk averse, and are rarely caught by surprise. They are proactive, and their goal is to have trucks out on the road well before a storm starts. They are willing to bear the costs of "false alarms" (sending out trucks unnecessarily, or too soon) in order to avoid being caught by a storm and not responding quickly enough. Since they make few of the latter errors, it is not likely that the value of an improved forecast will lie in preventing them. It is likely, however, that fuel, vehicle maintenance, and salt costs could be reduced through forecasts that allow supervisors to maintain safety and convenience on the Thruway with fewer false alarms.
- NWS forecasts are only one source of weather information for the supervisors. There is a DTN Corporation satellite system display in each maintenance office. Weather reports from other facilities on the Thruway are available hourly. Supervisors make their own observations of weather. Some patrol the road with pavement temperature sensors. Truck drivers report weather conditions back to their supervisors, and they also have some autonomy with regard to salting and more autonomy with regard to plowing.
- Situational factors are important in decision making. For example, decisions are affected by traffic volumes, time of day, and time of week.
- Supervisors must, implicitly or explicitly, make their own forecasts of the critical variable—pavement temperature. No one provides this information for them. It is obvious that pavement temperature is not the same as air temperature, and the treatment of the roadway, particularly the application of salt, depends on pavement temperature. The quality (and other dimensions of skill) of the predictions of pavement temperature and other weather factors made by the supervisors is critical to valuing forecasts, and is unknown. It would take a major effort to collect data on such forecasts and verify them.
- In an effort to improve decision making and to reduce costs and environmental damage, technology is changing. For example, Road Weather Information Stations (RWIS) are being tested and may be installed. Alternatives to salt which are less corrosive, but more expensive are also being considered. "Zero-velocity spreaders" which keep salt from scattering off the road are being tested.

Since NWS forecasts are embedded in a web of other, related, information, some of which is more timely and site specific than can be provided by NWS, extracting the impact of an improved forecast is complicated (Figure 3). The likelihood that improved forecasts will be implemented in a future when the decision process itself fundamentally changes, e.g., with new technology that presents different opportunities and costs to the supervisor, further complicates the problem.

5. Modeling for estimating the value of an improved forecast

From the case study, we learned about the decision processes of the Thruway supervisors, and the context in which their decisions are made. This is but one component required for an estimate of forecast value.

Estimation of the value of weather forecasts is a special case of the problem of valuing information (see Katz and Murphy, 1997, for a detailed discussion of the economic value of weather information). Decision theory provides an elegant method for making estimates of the value of information, but the validity of the resulting estimates rests on assumptions that are not always valid. The shakiest assumption of decision analytic models is that users of the information are rational and act optimally based on the information they are given. *Descriptive methods* are needed to incorporate realistic assumptions about decision making behavior into models for estimating forecast value. Our goal was to go beyond traditional economic models, exemplified by the snow removal model of Howe and Cochrane (1976), and base our estimate on a detailed case study of current practice. That case study has been described above. We felt that choosing a specific decision problem, limited to a particular geographical region, would provide the greatest likelihood to accomplish this goal.

5.1 Data and Modeling

Estimating the value of an improved forecast requires an estimate of the value of the current forecast, which is used as the baseline from which improvement is measured. Deriving an estimate of the value of an improved forecast is complex because it requires a prediction of how the improved forecast will be used in decision making, and a prediction of any future changes in technology that might affect decision making, among other factors. Such predictions are inherently clouded by uncertainty. Any model for estimating the value of an improved forecast therefore requires four components:

- A decision making model capable of mapping both current and improved forecasts, along with other important information, into decisions and, ultimately, actions. This requires data on forecasts (i.e., verification) that can in fact be mapped into decision processes.
- A detailed model of current and future forecast skill that specifies the conditional probability of specific weather events, given specific forecasts. The closer the match of specific weather events with decision criteria, the better the potential linkage of weather information with its decision value.
- A model of outcomes resulting from combinations of actions and subsequent weather events, under a variety of scenarios (e.g., traffic levels, section of roadway). This model would include the effect of alternative decisions on traffic flow, accident risk, and the fate and environmental and health effects of salt used on the roadway.
- A detailed model for valuing outcomes. This would include not only estimates of cost reduction, but estimates of the value of benefits such as reduced travel time and reduced accident rates.

We will summarize the data gathered for each of these model components here. There were serious complications at each step due both to the complexity of the problem and the lack of sources of relevant data sets that were both suitable for analysis and large enough to provide reliable estimates.

5.2 Decision making model

We developed a qualitative description of the decision making process (outlined above). This description is a necessary foundation for developing the quantitative model necessary for calculating forecast value. Such models can be derived from the record of decisions made, if it contains sufficient detail both about decisions made and about the conditions and other information at the time the decision was made. Appropriate data were not available (they rarely are). A second approach is based on simulated decisions based on hypothetical situations (see Cooksey, 1996). That would require more time and resources than were available for this study.

5.3 Model of current and future forecast skill

A basic requirement of any model of the value of an improved forecast is a quantitative estimate of that improvement. Furthermore, the detail of the estimate of skill must match the detail of the decision model. Such an estimate did not exist at the time we began the project, and it proved exceedingly difficult to obtain.

In a major effort to assess current skill in the vicinity of the Thruway, we merged a set of Rapid Update Cycle (RUC) 3-hour forecasts provided by Barry Schwartz of NOAA's Forecast Systems Laboratory (FSL) with corresponding hourly observations made by toll barrier operators that were provided to us by the Thruway authority. This resulted in a data set of 4532 forecast/observation pairs between 11/20/98 and 3/31/99. Since the forecasts and observations were not strictly comparable, assumptions had to be made in order to use the toll barrier observations to verify the RUC model forecasts. The forecasts were 3-hour accumulations of total precipitation (ptot) ending at the time of the forecast. The observers used verbal categories such as clear, flurries, light snow, rain, etc. After some experimentation, we categorized the RUC model output into two categories: "No precipitation" (ptot = 0) and "Any precipitation" (ptot > 0) categories. We also combined the verbal categories used by the toll barrier observers into two categories: "Clear" vs. "Rain or snow." (Note that for observers, "clear" describes the conditions of the road, not the sky.) Based on these categories, we were able to calculate an equitable threat score of .25, which is less than has been reported for other precipitation forecasts.

Although this analysis consumed many months, the results were unsatisfying. The data on current forecasts lack the detail we need to develop a model. For example, we have data for precipitation and snow amounts for only one lead time (3 hours), but the actions of supervisors require lead times of 0 to 8 hours, depending on the action, as well as forecasts of storm onset and duration. In addition, we need a finer grained analysis (more categories of forecasts corresponding to more categories of observations) in order to represent the forecasts that are used by the supervisors. We would also need to examine the data for more than one season. Furthermore, projections of future improvements in skill, resolution, and dissemination techniques are purely speculative. Before we can be confident about projections of future skill, a number of questions about *present* skill in forecasting onset, severity, and duration of snow and ice events relevant to decision making remain to be addressed.

In addition to an estimate of current and future skill, we needed a climatology of snow along the Thruway so that weather conditions could be represented accurately in modeling. No such climatology exists, so we began to assemble one by combining NWS records and observations made at toll barriers by Thruway personnel. Both sets of data had to be extracted manually from paper records. Thruway data were used to identify potential storms. The NWS storm record then had to be mapped to determine whether the Thruway was affected. We were able to obtain useful data for one season, but we would need many seasons to derive valid climatology. NOAA climatological data were examined for weather stations near the Thruway, but these data are organized by day, not by storm, so are of limited usefulness.

It was surprising to us that data on the climatology of the Thruway and data on the skill of current forecasts were not only unavailable but proved very difficult to generate. We had assumed when we started the project that obtaining weather data would be relatively easy and that we would concentrate on our strength, which is studying the way information is used. It turned out that much of our time and resources were consumed in obtaining and analyzing weather data (with disappointing results). We would strongly recommend a review of weather data archiving procedures and verification studies for supporting future studies of the use and value of forecasts.

5.4 Model of outcomes resulting from combinations of actions and subsequent weather events

We adopted a scenario approach to modeling outcomes. A scenario is constructed by specifying a) a section of roadway, time of day and week, b) storm intensity and duration over time, c) a forecast of storm intensity and duration, which is updated regularly, d) a model of the supervisor's response to the forecast and the current weather, e) assumptions about technology used, and f) a model of the outcome of various combinations of storm intensity and snowfighting activity.

Because of the variety of types of storms, road sections, and situations that affect the value of forecasts, many different scenarios would be required. Not only would storms of various durations and intensities have to be simulated, the conditions under which those storms occur have a significant effect on the supervisors actions. For example, weekend storms are treated differently from those occurring during the week. Storms in urban areas during rush hour are treated more aggressively than the same storm in a rural area at night.

If a representative set of scenarios could be constructed, and each scenario evaluated (assuming appropriate data were available with the requisite level of detail), then the results for each scenario could be appropriately weighted (weights depending on the relative frequency of the scenarios) and combined into an overall estimate of value. We realized that we would not be able to construct and evaluate all possible scenarios, so we focused on constructing a few important ones. It became apparent that the data needed to evaluated even one scenario were lacking.

5.5 Evaluating outcomes

We were able to obtain some information that would be useful in valuing outcomes from Thruway information, Federal Highway Administration data, and other sources. A paper by Vitaliano (1992) on the social costs of highway salting was particularly helpful. Information on a number of critical factors was not found, including , the role of weather in causing accidents on the Thruway or similar highways, exposure to risk of accidents (i.e., vehicle miles traveled) under different weather conditions, weather effects on travel time, and the improvements in accident rates and travel time resulting from snow removal. In addition, the historical weather record is based on a sparse network and does not include pavement conditions. The effect of changing technology on the value of outcomes is very difficult to predict. As is true for many activities, it is easier to quantify the costs of snowfighting than the benefits.

5.6 Summary of modeling effort

The limitations of the data we were able to collect included:

- Available data were secondary data not collected for modeling and the data do not demonstrate causation
- The sample sizes of the data sets we generated were small. One winter is small sample
- Data sets are on different geographic scales (Thruway section, county, NWS region, NWS station, toll barrier), so it is necessary to make interpolating assumptions in order to combine them
- Simlarly, the data sets are on different time scale (days, hours, storm)
- The data included significant gaps, missing data, inconsistencies

Due to the lack of relevant and useful weather information, the complexity of the decision process and uncertainty about potential outcomes and their value, there is a substantial gap between the available data and the data needed to establish reliably the value of an improvement in QPF. An estimate of value would therefore have to be based, in large part, on untested assumptions and judgments, and would have an extremely wide confidence interval. These factors led us eventually to abandon the goal of estimating in any meaningful way the dollar value of improved quantitative precipitation forecasts (QPF).

6. Conclusion

The case study results, provide insights, albeit qualitative ones, about the use and value of forecasts. We can make the following statements about the potential value of improved QPF forecasts.

- First, improved forecasts could help supervisors achieve their goal of being proactive. They want to avoid de-icing (treating a road that is already slick) in favor of anti-icing (preventing the road from getting slick in the first place).
- Second, improved forecasts could result in improved allocation of resources. Trucks could be sent to where they are needed and salt applied where it is most needed and not applied where it is not needed. One way to think of the supervisors' task is to convert snowy/icy miles of roadway into wet miles. Improved forecasts could be used to accomplish this with improved efficiency of operations, and reduced use of chemicals, labor, and equipment.

Beyond the potential to improve the efficiency of Thruway operations, improved forecasts have benefits for the end-users of the Thruway—passenger and commercial vehicles.

These benefits include improved traffic flow during bad weather, reduced fuel consumption, reduced accident rates, reduced environmental impact, and reduced health impact.

The data (including meteorological data) necessary to support credible and defensible quantitative estimates of the value of improved forecasts are lacking, returning us to where we had begun with forecast value conclusions dependent almost entirely upon basic assumptions and not the empirical data of the case. Responsible estimates would have confidence bounds so wide as to be useless. *A major lesson learned from this research is the critical importance of forecast verification data, data on actual decisions, and cost data for supporting studies of the value of weather information.*

To realize the potential of improved forecasts would require careful attention to the forecast products themselves (and their production and dissemination through the public and private sectors) *as well as* the role of forecast products in the specific context of actual decision making processes. The major implication of this study is that a more holistic approach to understanding and realizing forecast value is needed, i.e., one in which information (both of forecast skill and usage) centered on the decision process is collected in a much more intensive manner than is presently the case. Just as meteorologists need detailed knowledge of atmospheric conditions to project atmospheric conditions, so too do students of forecast value need detailed observational knowledge in order to realistically project forecast value. Absent such detail, studies of forecast value will simply be extensions of the assumptions brought to bear upon the study.

The WMO World Weather Research Programme (WWRP) has great potential to provide such a holistic approach. It recognizes advance in science and technology "will lead to societal benefits if and only if that research is successfully turned into products that are used by decision makers. Thus, the societal aspects of weather are an essential area of complementary research." It has recommended four areas of investigation necessary to gain WMO approval of projects under the WWRP. These areas are as follows:

- *Obtaining an improved understanding of the nature of the problem and the opportunity:* These include the costs of weather related events and who incurs those costs. Results obtained from this research, in conjunction with knowledge of predictability, etc., can help scientists to more effectively prioritize research objectives. More broadly, such research can provide information to help policy makers focus national priorities.
- *Use of forecasts by decision makers:* Even the most accurate forecast is of little value if it is not well used. To this end, it is important to understand what information decision makers could effectively use and also effective ways to communicate that information. Research in this area can help to identify those conditions necessary and sufficient for forecasts to contribute to the needs of decision makers.
- *The process of transitioning research to the operational community:* This process focuses on the needs of forecasters seeking to provide information of use to decision makers. Both the structure of the process and the content of the information being transferred should be evaluated from the standpoint of the penultimate goal of producing useful products. Thus in addition to research on the use of forecasts, appropriate research might include the institutional structures through which the transfer process takes place.

- *Evaluation of forecasts:* There are many measures of forecast "goodness." Such evaluations are an important component of the program's ability to assess progress with respect to its goals.

The results of such research have significant potential to inform decision makers who seek to prioritize public expenditures among myriad competing objective, of which weather is but one are among many, as well as those decision makers within the weather community who face difficult choices among many meritorious competing priorities. Absent such information, weather-related priorities will likely be set in an ad hoc fashion, potentially limiting the ultimate societal benefits associated with investments in research and technology.

Thus, the major conclusion of this study is guidance to the meteorological community as to what sorts of data and methods would be necessary to improve the knowledge base of forecast use and value. If the potential societal value of scientific research is to be realized, and if forecast value is to play anything more than a secondary role in weather policy decisions, then an ongoing effort to support studies of forecast use and value will be required. The WMO WWRP provides some guidance in that direction.

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