Integrated Framework for Quantifying and Predicting Weather-Related Highway Construction Delays

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Abstract: Constant exposure to the environment makes highway construction highly dependent on weather. However, highway construction contracts are often unclear about the potential influence of weather-related delays on highway construction project schedules. There is a need to discourage litigation arising from weather-related delays by including in contracts a reasonable number of nonwork days as a consequence of adverse weather and providing an equitable criteria for the course of action when the predictions in the contracts turn out to be inaccurate. To address this need, an integrated framework consisting of the following two key components is proposed: (1) identification of attributes of weather that cause construction delays and (2) generation of synthetic weather sequences using a stochastic weather generator to quantify and provide probabilistic forecasts of weather threshold values. The utility of this framework is demonstrated through its application to construction work on a project in Texas. The use of probabilistic forecast of construction delay attributes provided by a semiparametric weather generator in this research is an example of interdisciplinary study to help address this problem. The result of the research is better decision support for agencies who wish to author contracts that more equitably allow for the influence of weather during construction.

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Introduction

Weather can have a dramatic effect on a construction project. Highway construction is particularly vulnerable to weather than other types of construction because of constant exposure to the environment. Ambient conditions related to air temperature, precipitation, and wind velocity cause considerable difficulties and delays during highway construction. The most significant highway construction operations affected by weather are earthwork, paving, and structural work such as bridge construction or work that involves the use of heavy cranes. The variation in weather patterns throughout the United States makes it difficult to standardize risk allocation for weather in contract documents. The purpose of this study was to understand how weather affects highway construction and to develop a framework for predicting a reasonable number of nonwork days as a consequence of adverse weather. The results of this research are intended to assist highway agencies in more equitably allocating risk for weather-related delays in their construction contracts before they occur.

Advance understanding of the effects of weather on any type of construction can potentially reduce disputes and claims caused by delays. In the case of *McDevitt and Street versus Marriott Corporation* (Bruner and O'Connor 2002), the owner and the contractor used two different methods to calculate the expected weather. The judgment did not address right or wrong, but rather whose method was more reasonable. This research aims to help define "reasonable" prior to commencement of work.

This paper presents an overview of select prior work in this area, followed by a description of the "attributes" that capture weather-related delays. A nonparametric stochastic weather generator developed for generating synthetic weather scenarios conditioned on large-scale climate forecast is then presented. Finally, results from a case study in Texas are presented.

Overview of Prior Work

Weather prediction can provide important input into highway construction scheduling and the contract provisions that allocate risk

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J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

Table 1. Example of Monthly Anticipated Adverse Weather Delay Work Days

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sept.	Oct.	Nov.	Dec.
10	9	9	8	7	7	7	5	6	5	7	8

for the impacts of weather on construction. If an extension of work is granted by the owner due to inadequate weather analysis on the part of the contractor, the resulting delay might push the project into the winter months. Alternatives such as acceleration by the contractor can result in considerable cost increases for the project and are therefore undesirable. Several studies have been conducted that show the importance of weather analysis in the preplanning stage of construction projects. The conclusion from one such study was that "normal anticipated weather" as well as the magnitude of "delays caused by unusually severe weather conditions" should be clearly defined (Hinze 1989). Another study developed a decision support system for quantifying the impact of rainfall on productivity and duration for highway construction operations (El-Rayes and Moselhi 2001).

A study by the National Cooperative Highway Research Program (NCHRP) showed the impact of different types of weather on different highway construction operations [National Cooperative Highway Research Program (NCHRP) 1978]. According to this study, 45% of all construction activities are affected to some degree by weather, resulting in additional costs that run into billions of dollars annually. The South Dakota DOT adopted a pragmatic solution by combining their construction records with weather records to determine weather thresholds in order to determine the expected adverse weather days and expected working days for six zones and two construction type categories [South Dakota DOT (SDDOT) 1997]. The types of weather effects considered are precipitation (rain, sleet, snow, and ice), air temperature extremes, wind velocity, and soil temperature. Procedures were developed for using this information to calculate contract time and determine time extensions for adverse weather.

The Federal Highway Agency (FHWA) provides funds and oversight for the construction of the Federal highway system. Even though individual agencies have their own means and methods to deal with delays due to weather, the FHWA lacks a consistent methodology for projects exposed to different weather patterns in various parts of the United States. Weather patterns in the state of Washington differ from the weather patterns in the states of Colorado, Florida, or Pennsylvania. Thus, there is a need for a suite of "attributes" that realistically captures the construction delays due to weather, and is portable across sites with different weather regimes. Furthermore, there is a need for a modeling framework to quantify and predict these attributes using a stochastic weather generator.

Weather-Related Contract Provisions in Highway Construction

The overall goal of a contract is to allocate work, allocate risk, and eliminate confusion between the parties. In highway construction, contracts typically follow the guidelines set forth by the AASHTO. However, similar to any standard, each highway agency may have contract provisions or alterations from the AASHTO guidelines because of differences from the norm and/or preferences of the state. Two key points are the contract provisions relating to time and the contract provisions defining abnormal weather.

There are three primary methods for dealing with schedule issues in highway construction: (1) calendar days; (2) working days; and (3) completion days. When the work is on a calendar day basis, one calendar day of contract time will be assessed for each calendar day from the date that the contract time starts until completion including Saturdays, Sundays, and holidays. Less than full-time charges may be made on those days when conditions, which are beyond the control of and unknown to the contractor, make it impossible to perform the work on items controlling the completion of the work with full, normal efficiency. Generally, less than full-time charges may be allowed for inclement weather only when the engineer directs the contractor not to work for the safety of the traveling public. When the work is on a working day basis, one whole day of contract time will be assessed for each working day on which work can be effectively executed during six hours or more of the day. One-half day will be assessed for each working day on which the work can be effectively executed for at least 2 h but less than 6 h of the day. Contract time is generally not assessed when the work can be effectively executed for less than two hours. Saturdays, Sundays, and holidays are assessed as working days when the contractor utilizes such days for performing the work. When the contract specifies a completion date, all work under the contract shall be completed on or before that date. For some highway agencies, no extension of the completion date will be allowed for inclement weather, foreseeable causes, or conditions under the control of the contractor. However, this is not always the case. Most contracts are written so that there is a contract date required for completion but also provide for adjustments for excusable delays.

DOTs for each state determine their contractual approach to allocating risk for weather. Hinze (1989) found that 60% of the agencies include provisions for weather delays in the contract time, yet only 22% of the agencies define what signifies abnormal weather. This ambiguity has led to litigation over the years (Xi et al. 2005). This type of risk can be reduced by including expected weather days in the contract and clearly explaining how these expected weather days are calculated.

One method to equitably allocate weather risk in contracts is to define the expected number of nonworking days due to weather for each month directly in this contract. Table 1 provides an example of how these days are specified in a contract. This method presents a clear approach to defining weather delays in the contract for all parties. A challenge with this method is that delays are extremely specific to the type of construction activity being performed. Therefore, different delay results can be expected when the start date of a project changes significantly. For example, since earthwork is affected greatly by precipitation, it would be beneficial as far as the sheer number of delay days for earthwork to avoid that type of construction during the wettest months of the year. A second challenge is that once the delay days are exceeded, the owner inherently agrees to grant an extension of time to the contractor. However, if there is no definition of how these numbers were derived, disputes will arise as to what qualifies as a delay day. This research provides a modeling framework to quantify and predict these delays using a construction schedule analysis and a stochastic weather generator. While it is impossible to predict weather and very difficult to predict the actual sequence of

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

Table 2. Effect of Weather on Highway Construction Activities [National Cooperative Highway Research Program (NCHRP) 1978]

Construction operation	Low temperature	Rain	Sleet	Snow	Ice	Frozen ground	Wind
Traffic handling	L	M	S	S	S	L	L
Layout and staking	M	S	S	S	S	M	M
Clearing and grubbing	L	M	M	M	M	L-M	L
Material delivery and storage	L-S	S	S	S	S	L-M	L
Excavation	L	S	M	M	M	M	L
Embankment construction	M-S	S	S	S	M	M-S	L
Structure site grading	M-S	S	S	S	M	M-S	L
Pile driving	L	M	M	M	M	M	L
Dredging	M-S	L	L	L	S	L	M
Erection of coffer dams	M-S	M	M	M	S	L	L-M
Formwork	M	S	S	M	S	L	L-M
Steel erection	M	S	S	M-S	S	L	M-S
Placing of rebar	M	S	S	S	M-S	L	L
Mixing and placing concrete	S	S	S	M	M	L	L
Curing concrete	S	M	M	M	S	L	M
Stripping forms	L	M	M	L	M	L	L-M
Backfill	S	S	S	M	M	M-S	L
Base placement	S-M	S	M	M	M	M-S	L
Asphalt paving	S	S	S	S	S	M	L
Landscaping and seeding	S	S	S	S	S	S	L
Painting	S	S	S	S	S	—	M
Fencing	L	M	M	M	M	M-S	L
Lighting	M	M	M	M	M	L	L
Signs	L	M	M	M	M	M	M

Note: S=severe; M=moderate; and L=little.

construction in the field, transparently including in the contract the expected number of weather days and the manner by which they were calculated provides an opportunity to reduce weather-related delay claims.

Weather Effects on Construction

Table 2 summarizes the result of adverse weather on work, labor, equipment, and materials. Based on these data, one can expect to have moderate to severe problems due to precipitation for all construction operations. Although the effect of hot temperatures was not found to be significant, there is a moderate to severe effect when cold temperatures are present during construction. Finally, wind speeds upward of 48 km/h (30 mi/h) can cause a moderate to severe effect on some construction operations, especially with regard to labor effectiveness and crane operations.

With this information, it is easy to conclude that depending on the type of construction activity, all types of weather can create an adverse effect. However, the NCHRP study states that the most adverse conditions are created by rain or snow in combination with wind and/or cold temperatures. Therefore, as shown in Table 2, each weather condition has an individual effect on different types of construction. The effect is magnified with a combination of weather conditions occurring simultaneously.

Precipitation

Of all types of weather, precipitation acting alone affects construction the most significantly. When precipitation in the form of rain occurs on a construction site, saturated soil conditions and flooding can cause numerous problems with materials as well as human and equipment productivity, even after the rain stops. Rain has a pernicious impact upon site conditions extending well beyond short-term work stoppages during precipitation to longer term impact of surface runoff that can: (1) inhibit site access by making access roads impassable; (2) inhibit site work by flooding excavations and low areas; (3) increase the moisture content of soils so as to require additional compaction efforts; (4) raise groundwater tables; (5) cause erosion requiring regrading; and (6) damage installed work (Bruner and O'Connor 2002). The duration of the delay depends on the amount of precipitation as well as the duration and timing of the event (El-Rayes and Moselhi 2001). For example, a storm event that produces 25.4 mm (1 in.) of rain in an hour will have a different effect on a jobsite than an event that produces the same amount of rain in a day. Likewise, a precipitation event that occurs in Seattle is likely to have a noticeably different impact than the same weather event in Phoenix. Snowfall effects on construction are also similar.

Not only does precipitation affect the conditions of the site, but also it controls the type of work that can be done during or after a weather event. For instance, some DOT specifications state that asphalt paving cannot be laid on any wet surface. Therefore, if it rains shortly before or during a paving operation, the work will be delayed. Likewise, wet weather has an adverse effect on concrete paving as well. Therefore, precipitation is considered the most significant of all weather events.

Temperature

Air temperature is well defined in construction contracts. Standard specifications include minimum and maximum temperatures

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

for many construction materials including concrete and asphalt. However, temperature directly affects the productivity of the workers as well [National Cooperative Highway Research Program (NCHRP) 1978]. The NCHRP study notes that extremely high temperatures typically result in productivity losses of 10 to 30% while cold weather drops the productivity from 90% at 4.44°C (40°F) down to a dismal 10 to 20% at −40°C (−40°F). Most construction materials have such thresholds. However, temperature is one type of weather effect in which construction does not necessarily have to be delayed when exceeding these thresholds, as long as the project can absorb expenditures for measures such as heated enclosures.

Wind Velocity

High wind velocities may affect certain construction operations, but equally important is the effect of wind on temperature. It is well known that the effect of a combination of low temperature and wind causes "wind chill" which can reduce productivity and can even be dangerous to workers. Wind alone can also cause several construction operations to shut down. For instance, when structural beams are being placed for bridge work, high wind conditions can make the crane unstable and lead to accidents. High wind conditions may also cause fresh concrete to dehydrate on the surfaces and develop cracks. The following legal passage from Bruner and O'Connor (2002) illustrates the total effect wind can have on construction. Wind at speeds of 32.2 km/h (20 mi/h) or more can reduce labor productivity by 30 to 40%, particularly in vulnerable labor activities involving the installation of exposed materials such as erection of structural steel and curtain wall, installation of floor decks and roofs, exterior painting, and other exterior activities. Therefore, wind not only affects the temperature and construction operations such as crane work, but it also affects materials and material processes.

Soil Temperature

Although soil temperature may not directly affect labor productivity, it has an effect on operations and equipment. The biggest impact of soil temperature is on earthwork. Frozen ground magnifies the difficulty of movement and compaction of soils. Field experience has shown that neither cohesive nor granular soil can be compacted satisfactorily while frozen [National Cooperative Highway Research Program (NCHRP) 1978]. Frozen soil may also limit asphalt and concrete work. Finally, equipment productivity is reduced when working with frozen soil conditions. As cold weather affects the operator of the equipment, soil conditions affect the effectiveness of the equipment.

Weather Attributes That Cause Delay

This research developed a threshold matrix that is central to quantifying the delays associated with weather effects on construction. The matrix is the analytic engine for the framework developed in this research. The thresholds were developed through a research study for the FHWA (Xi et al. 2005). The thresholds represent the maximum quantity of a certain weather event that can occur while performing or immediately prior to performing a particular construction activity; weather events exceeding this threshold constitute reasonable grounds for a nonwork day. Two questions guide the structure of the threshold matrix:

	Concrete Paving	Asphalt Paving	Structural	Mass Excavation	Grading
Precipitation	2.54 millimeters (0.1 inches) during pour, or significant rain prior to pour	No moisture allowed during paving and base must be dry	6.35-12.7 millimeters (0.25 -0.5 inches) needs to conform to concrete paving threshold	6.35-12.7 millimeters (0.25 -0.5 inches)	6.35-12.7 millimeters (0.25 -0.5 inches)
Temperature	Below 0 degree Celsius (32 degrees Fahrenheit) or above 32.22 degree Celsius (90 degrees Fahrenheit)	Between 0 degree Celsius (32 degrees Fahrenheit) and 10 degree Celsius (50 degrees Fahrenheit)	Below 0 degree Celsius (32 degrees Fahrenheit)	None	Below 0 degree Celsius (32 degrees Fahrenheit)
Soil Temperature	The night prior to pouring the air temp. below -5.55 degree Celsius (22 degrees Fahrenheit) causing ground to freeze	Between 0 degree Celsius (32 degrees Fahrenheit) and 10 degree Celsius (50 degrees Fahrenheit)	None	Freezing	Freezing
Wind Velocity	Above 40 kilometers per hour (25 miles per	None	55 kilometers per hour (35 miles per hour)	None	None

Fig. 1. General threshold matrix (requires calibration to individual project conditions)

1. What types of weather events affect construction significantly?
2. What types of construction operations are associated with the critical path?

Fig. 1 presents the threshold matrix in its entirety. The FHWA being a national agency, developing an exact threshold matrix that can be applied to any project nationwide is ineffective because the range of each threshold will be too wide to be of any practical use. For example, soil types play a large role in determining the effect of precipitation on a project. If the soil type in a project is entirely sand and gravel, then precipitation will infiltrate quickly and work can resume at a faster rate. However, if the site's soil is primarily made up of clay, then infiltration will take much longer and muddy conditions or ponding may occur depending on the grade of the land. Therefore, the framework seeks to guide the owner and the contractor to make suitable decisions regarding the selection of thresholds for each project. The framework is intended as a guideline to follow in order to better define the thresholds appropriate for each project.

The framework serves as a guide to select the parameters for any project. As every project is different, factors such as geographic location, climate, construction materials, contract type, and schedule all have a large impact on the selections made in the decision framework. In order to have a standardized method of predicting weather delays, tacit knowledge and engineering decisions about the dynamics of the aforementioned factors should be considered. For example, an engineer should adjust thresholds that are reasonable for the climate during the time of year when the work is to be completed.

Fig. 2 is a simple flowchart designed to guide the user through the decision framework. For projects in which the impact of the weather is likely to be significant, each step of the process should be followed. For projects in which weather plays only a minor role in the determination of contract time, the design engineer or contract writer may consider only one or two critical path items in months where weather is likely to have a negative impact on the

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

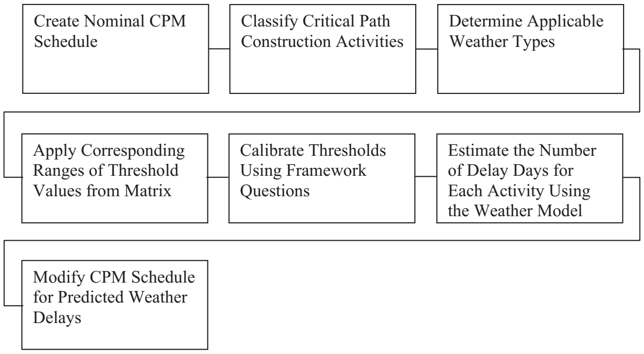

Fig. 2. Decision framework flowchart

project schedule, thereby greatly reducing the effort required to implement the decision framework.

A critical-path method (CPM) schedule is needed to determine the "nominal schedule," a starting point for the decision framework. The nominal schedule should be initially created with no adjustments for weather delays. There can be any number of tasks in the schedule. However, each task associated with one of the five particular categories of construction that appear in the matrix shown in Fig. 1 should be noted as it will be analyzed for weather delays in the process.

For each construction task on the critical path schedule, the pertinent weather conditions that may cause a delay must be identified. The four weather types to be considered are precipitation, temperature, soil temperature, and wind velocity. The threshold matrix provides the basic threshold value, which will often need modification due to conditions specific to the project site and geographic location.

Calibrating Thresholds for Weather-Related Delay

There are ranges of values in the threshold matrix for some categories. This is due to variations in site conditions and other parameters. In addition, some of the single value entries in the matrix may be adjusted for similar reasons. A series of questions should be reviewed for each category of construction, in order to adjust the thresholds in the matrix. The questions are as follows.

Earthwork: Mass Excavation and Grading

1. In which season of the year is earthwork scheduled to take place?
2. What is the soil type(s) on the site?
3. What is the slope of the site?
4. Will the site have adequate drainage during construction?
5. What is the depth of the frost line?

The first of the earthwork questions is concerned with legal and contractual issues. Legal considerations require that a contractor must be unable to reasonably foresee a weather event for it to be considered abnormal. The time of year and geographic location are important parameters to consider when predicting normal weather delays.

Questions 2 to 4 deal primarily with precipitation thresholds. These questions are geared toward the drainage conditions of the site. For example, a flat site consisting mainly of clay will need a lower precipitation threshold than a well drained site with sandy soil. In addition, the direction of the slope of the site may be important. The contour of the site may beneficially drain from one area of construction into another poorly drained area causing negative results. Careful considerations of the construction-site topography and soil conditions are needed to make a well-informed decision regarding these thresholds.

Finally, the last question relates to the depth of the frost line. This question is aimed more toward projects with a large amount of mass excavation or grading. The issue the contractor needs to consider is the time of the year or duration of the earthwork. Is the earthwork to extend into the winter? Areas that have very shallow frost depths are easier and far less expensive to keep earthwork moving throughout the entire year since the frozen layer can be peeled off if needed to continue excavation. Grading, on the other hand, is difficult because the top several inches are critical in grading operations.

Asphalt and Concrete Paving

1. In which season of the year is paving scheduled to take place?
2. Are resources (time and money) available to take corrective actions in the case of weather that will affect paving activities?
3. What is the drying capacity of the base below the paving layer?

Mechanical and physical properties of concrete make it possible to create a better environment for curing in spite of unfavorable ambient conditions. For instance, if the ambient air temperature is cooler than desirable, warm water can be added to the concrete mix which will raise its temperature during the initial stages of curing. Also, if the temperature on the night of the pour is predicted to be colder than desirable, concrete can be covered in order to preserve the heat given off by hydration reactions between cement and water. There are many other methods to create a desirable environment for concrete to cure. However, many of these methods are expensive and can lengthen the planned task duration, and must therefore be considered when setting a threshold value for no-work day.

Both asphalt and concrete require a dry or nearly dry base before application. Question 3 addresses this issue specifically. Although the threshold matrix indicates that concrete requires that no more than 2.54 mm (0.1 in.) of precipitation occur during the pour and that significant rainfall cannot exist in the period before the pour, there is inherent judgment involved. How much is significant and how long after a rainfall does the contractor have to wait prior to pouring will vary with site conditions. The threshold for paving differs from the threshold for earthwork, simply because the contractor needs a dry or virtually dry base to continue with a concrete pour.

Structural

1. What type of material is used in the design of the structure(s)?
2. What type of foundation is required by design?
3. Is there any scheduled crane work?
4. Is there any sort of wind break around the structure?
5. In which part of the year is structural work scheduled to take place?

The first two questions in this section deal with relating the structural work to other categories and therefore other thresholds. For instance, Questions 1 and 2 ask about the design of the structure and the foundations. If the bridge is concrete, then the work

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

must adhere to the thresholds that correspond to concrete. Also, if the foundations are concrete and require excavation, then consideration must be given to both sets of thresholds.

Questions 3 and 4 are primarily to get the contractor to consider about the effect of wind on construction. The schedule will predict when the crane work needs to be done and the wind should be considered heavily during those times. Also, because wind decreases the hydration on the surface of curing concrete, cracking can occur from high wind conditions.

Weather Model

Each threshold value in the threshold matrix represents a weather condition that may delay the relevant construction task. A weather model is used to estimate the number of days in each month when the particular adverse weather will occur. From this prediction, the construction schedule in the original nominal schedule is modified to include the weather effects. Implementing the weather model involves the following two steps:

1. Obtain the daily weather data for the construction site from the National Climatic Data Center (NCDC) website (http://www.ncdc.noaa.gov/oa/climate/stationlocator.html); and
2. Run this weather data through a stochastic weather generator.

From the simulated weather sequences, estimate the probability-density function (PDF) of the events of interest [i.e., number of days with precipitation >12.7 mm (0.5 in.), and number of days with temperature $<0°$C Celsius (32°F) etc.] and consequently create cumulative distribution function (CDF) plots of the events for convenient use.

Stochastic Weather Generator

Traditional weather generators [e.g., Richardson 1981] use a Markov chain to model the precipitation occurrence (i.e., wet or dry day) and an appropriate PDF (usually, gamma) to generate the rainfall amount if it is a wet day. Conditioned on the precipitation state (i.e., wet or dry) the other weather variables (temperature, wind speed, etc.) are generated based on a multivariate auto regressive (MAR-1) model. The parametric approaches are easy to implement and have a rich background, but they suffer from the following main shortcomings. (1) The MAR framework requires normality of the data. If the data are not normally distributed, they have to be transformed to normality. With several variables and seasons (e.g., months), this transformation task can be quite difficult. Furthermore, good performance of the model in the transformed space does not guarantee the same in the original space. (2) For the rainfall amounts potential nonnormal features such as bimodality, if exhibited by the data, cannot be captured by the limited suite of PDFs.

Nonparametric methods are data driven and are largely assumption-free unlike the parametric counter part described above. There are several nonparametric weather generators (see, Rajagopalan and Lall 1995), but the *k*-NN (i.e., *k*-nearest neighbor) time series resampling approach (Lall and Sharma 1996; Rajagopalan and Lall 1999; Buishand and Brandsma 2001; Yates et al. 2003) is shown to be simple, flexible and robust in terms of capturing the true variability of the observed data.

This study uses semiparametric weather generator (SWG) model that combined the parametric and nonparametric approaches, retaining the strengths of both these methods. The model development and its utility are described in detail in Apipattanavis et al. (2007). A brief description of the implementation methodology is provided here for the benefit of the readers. To simulate daily weather for a given day, say June 1, a 15-day window is selected and centered on this day. The steps are as follows:

1. A Markov chain of order-1 is fitted to the precipitation occurrence data on all the days within this window from the historical period. The Markov chain provides the probability of transiting from a given state (wet or dry) on previous day (May 31) to the current day. The transition probabilities are used to generate the state of precipitation on June 1.
2. The vector of weather variables are generated from the conditional PDF

$$f(x_t|x_{t-1},S_t,S_{t-1})$$

   where x_t and x_{t-1}=weather vectors on day "t" and "$t-1$," respectively, and S_t and S_{t-1}=precipitation states on day t and $t-1$, respectively. The vector (x_{t-1},S_t,S_{t-1}) is the "conditioning vector." To accomplish this, k historical days within the 15-day window over the historical period are identified that are "similar" to the "conditioning vector" at the current day "t."
3. From the k nearest historical days (or nearest neighbors), one is selected based on a weight function that gives highest weight to the closest neighbor and least to the farthest.
4. Steps 1 through 3 are repeated for each day of the year.
5. From the generated weather sequences, events of interest that impact construction delay are computed and consequently, their PDFs are estimated.

To generate weather sequences based on a seasonal forecast, the above framework is easy to modify. In that, in Step 2, days within the 15-day window from years that are similar to the current seasonal forecast are given more preference than the others (Clark et al. 2004). This study uses the seasonal precipitation forecast of the International Research Institute for Climate and Society (IRI); (http://iri.columbia.edu/climate/forecast/net_asmt/). The IRI forecasts are provided as percentage likelihood of $A:N:B$ format, where A denotes percent chance of above-normal rainfall, N denotes percent chance of near-normal rainfall, and B denotes percent chance of below-normal rainfall. These three categories are defined by the terciles of the historical distribution of rainfall ($A:N:B=33:33:33$) for the location and period in question. For example, a forecast of $A:N:B=40:35:25$ for an area means that there is a 40% chance of rainfall being above normal, 35% chance of rainfall being near normal, and 25% chance of below normal precipitation. The above method can also be used to generate weather sequences simultaneously at several locations in a region, thus, maintaining the spatial correlation. As mentioned earlier, these techniques are described in detail in Apipattanavis et al. (2007) and comprehensively demonstrated for a case study in Argentina. This has also been applied to several case study sites in the United States (Xi et al. 2005) including the site described here in the following section and demonstrated the ability of method in capturing the statistical properties of the historical data. The readers are referred to these two publications for the results. Only the relevant figures are shown in this paper.

Case Study Results

The case study described in this paper is for a project in Tex. called the Brazoria Tour Loop Road, for which the nominal schedule of activities likely to be affected by weather is shown in

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

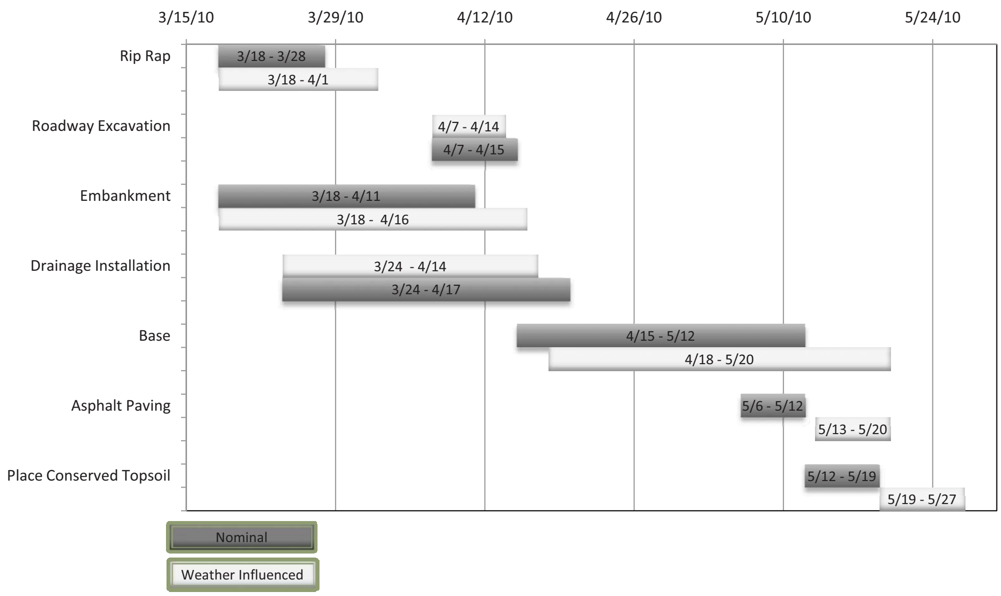

Fig. 3. Nominal and weather-influenced schedules for Brazoria Tour Loop Road

Fig. 3. The nominal schedule for the project was created on December 1, 2002, approximately three months prior to the start of construction.

Pertinent weather graphs obtained using the weather model for this region are displayed in Figs. 4–6. Daily weather sequences were generated and conditioned on the IRI seasonal precipitation forecast (wetter than normal, $A:N:B=40:35:25$) for March–May 2003 issued in December 2002. From these sequences, the events of interest were estimated and consequently their PDFs shown in the above figures. Table 3 shows the construction tasks for this project along with corresponding weather thresholds selected by the engineer who established the schedule. Note that some thresholds vary from those displayed in Fig. 1, because they were calibrated based on the judgment of the engineer familiar with the site conditions. Table 3 also shows the number of days in each month that are expected to have weather conditions in excess of the thresholds.

Using the logic displayed in the nominal schedule, it is clear that some tasks have extended timelines and/or a shift in the starting dates. For example, the riprap portion of the project was nominally scheduled for 9 days (9 swd). At 80% probability level, Fig. 4 indicates that 5 days in March are expected to have precipitation in excess of 12.7 mm (0.5 in.). With 31 days in March, the number of delay days expected for the riprap operation is $(5/31)\times 9$ which are approximately 1.5 delay days, which is rounded up to two delay days. An assumption in this calculation is that the five adverse weather days are uniformly distributed over the entire month. Considering weekends, the schedule was extended from March 28 to April 1 as shown in Fig. 3. In this case, this delay does not influence any other tasks, which may not always be the case. Fig. 3 also shows the weather-influenced schedule for each activity based on the estimated delay days derived from the calibrated weather thresholds.

Limitations of This Research

Some important factors that have not been addressed in this research include the effect of combinations of weather events, such as heavy rain followed by several cloudy days. Another example is heavy snowfall that results in several days or weeks of construction delay. Nonetheless, the general threshold matrix provides a decision aid for agencies that currently do not adequately address weather-related delays in highway construction contracts. The limitations of the framework proposed in this research are addressed below.

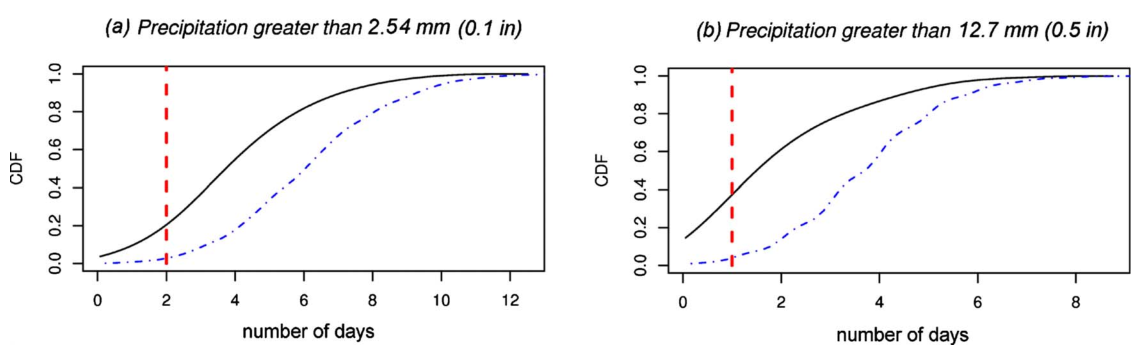

Fig. 4. Weather graphs for the Brazoria Tour Loop Road (March 2003). Solid line and dot-dashed line represent the climatological CDF and the precipitation forecast CDF, respectively. The vertical dashed line indicates the observed number of days.

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

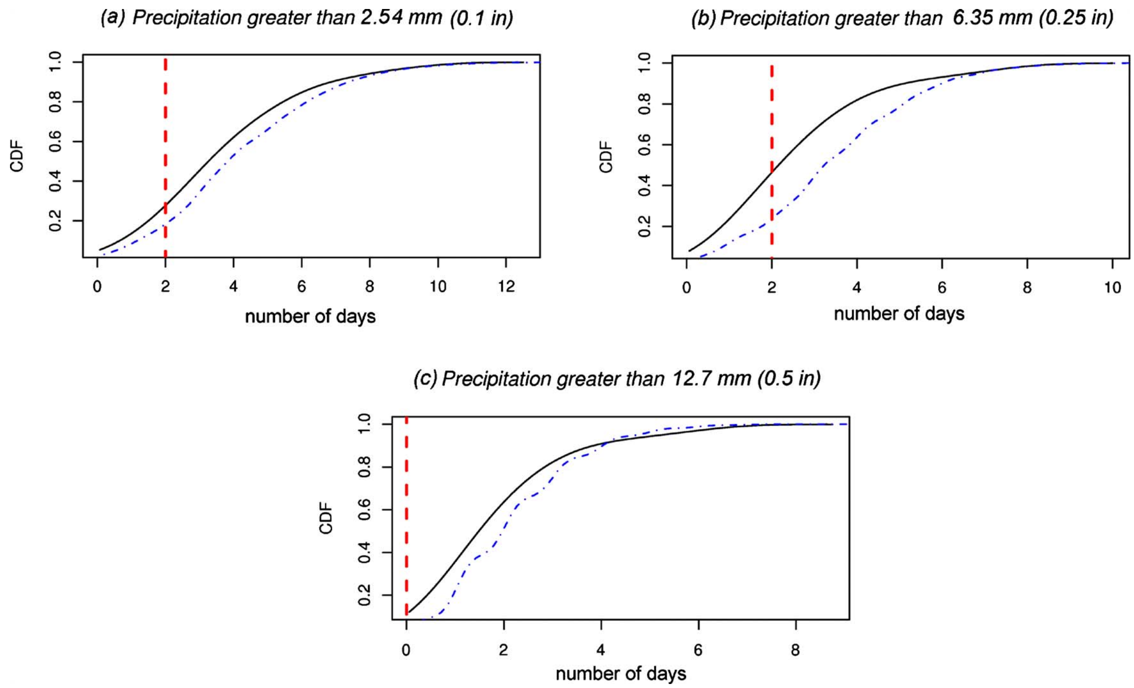

Fig. 5. Weather graphs for the Brazoria Tour Loop Road (April 2003)

1. Threshold values are included only for five general construction types. Weather related delays are generally considered for activities on the critical path because they are likely to affect the project completion date. Therefore, this research focuses on construction types that are typically associated with the critical path. However, it is quite likely that there will be construction activities on the critical path that cannot be categorized into one of the five construction types in the threshold matrix, for example, specialized construction activities performed by subcontractors. Engineering judgment will have to be used to estimate the thresholds for such activities.
2. The ranges of thresholds do not cover the conditions in all 50 states. The range of values provided in some thresholds in the general threshold matrix is aimed to cover a large part of the United States. However, for regions that have a dramatically different climate than what is considered "normal" for the majority of the United States, these ranges may not be wide enough to cover the spread. On the other hand, if the ranges were widened to fit all climates in the United States, then the owners and contractors for projects in regions with "normal" climate will have a difficult time deciphering the correct threshold to use within the range. Therefore, the trade-off for making the decision framework user-friendly is that the framework is not applicable to regions on either end of the range of climate severity. In addition, the thresholds only take into account standard practice for materials. For instance, there are cold weather curing techniques for concrete which allow work to progress outside the thresholds, albeit at a higher cost.
3. Whether or not the validity of the threshold values can be verified statistically remains to be seen. The data needed to statistically validate the decision framework presented herein do not exist or are difficult to uncover. As a result, the threshold matrix could not be verified or validated. A recommendation resulting from this limitation is that the FHWA document delays attributed to weather on each project after the implementation of this framework. The data can then be used to update the ranges of the threshold matrix, raising the confidence level associated with the matrix over time.

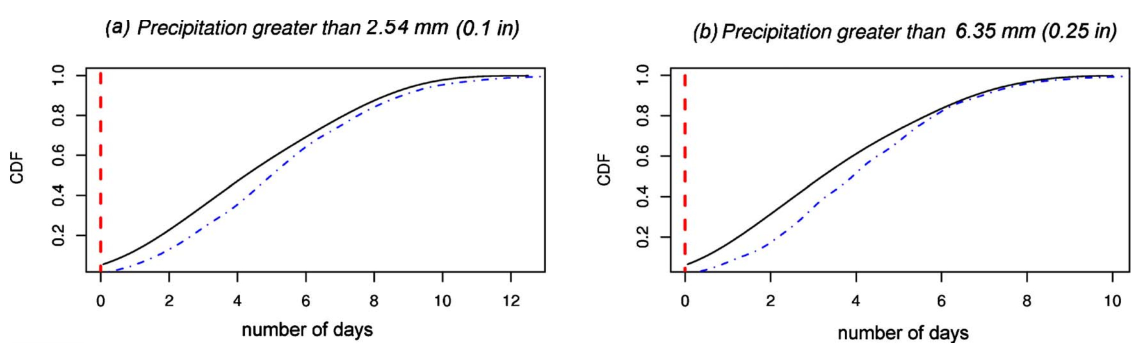

Fig. 6. Weather graphs for the Brazoria Tour Loop Road (May 2003)

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168

Table 3. Expected Number of Delay Days for the Brazoria Tour Loop Road

	March 2003	April 2003	May 2003
Riprap	5 wd		
Mass excavation	9 swd		
Threshold: 12.7 mm (0.5 in.) rain	1.5 dd		
Roadway excavation		3 wd	
Mass excavation		6 swd	
Threshold: 12.7 mm (0.5 in.) rain		0.6 dd	
Embankment	5 wd	3 wd	
Mass excavation	10 swd	9 swd	
Threshold: 12.7 mm (0.5 in.) rain	1.6 dd	0.9 dd	
Drainage installation	8 wd	6 wd	
Mass excavation	6 swd	10 swd	
Threshold: 2.54 mm (01. in.) rain	1.5 dd	2 dd	
Base		5 wd	6 wd
Grading threshold: 6.35 mm (0.25 in.) rain		12 swd	8 swd
		2 dd	1.5 dd
Asphalt paving		6 wd	8 wd
Threshold: 2.54 mm (0.1 in.) rain		1 swd	4 swd
		0.2 dd	1 dd
Place conserved topsoil			6 wd
Mass excavation			6 swd
Threshold: 6.35 mm (0.25 in.) rain			1.2 dd

Note: wd=expected number of adverse weather days; swd=number of scheduled work days; and dd=number of expected days of construction delay.

Summary and Discussion

The main contribution of this study that distinguishes it from the prior work is the weather prediction model based on recorded local weather, and a means to standardize the threshold values for no-work days depending on different weather conditions and construction types. The stochastic weather generator framework developed in this research is parsimonious, flexible, and easy to implement. The framework can also be easily coupled with a weather or seasonal climate forecast to generate synthetic weather sequences consistent with the forecast.

Much of the litigation resulting from weather delay disputes is based on the lack of adequate definition of terms in the contracts. Whether a day with adverse weather is workable or not depends on the weather thresholds assumed. In addition, the extent of expected adverse weather delays depends on many factors, such as the length of observed data used, the simulation model used, and the confidence interval used in the statistical analysis of the weather data. These factors should all be addressed clearly in the contract to avoid legal arguments over the definitions. When a contract is signed, there should be agreement between the parties on what constitutes an adverse weather day, and the "reasonable" number of adverse weather days that are expected in each phase of the project. Besides a more comprehensive contract, a weather model such as the one presented in this study can greatly improve the understanding of the parties in the contract about how weather is likely to influence the baseline schedule. Such an understanding will aid in reducing the number of disputes arising from weather-related delays.

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References

Apipattanavis, S., Podestá, G., Rajagopalan, B., Ritz, R. W. (2007). "A semiparametric multivariate and multisite weather generator." *Water Resour. Res.*, 43, W11401.

Bruner, P. L., and O'Connor, P. J. (2002). *Bruner & O'Connor on construction law*, Vol. 4, West Group, St. Paul, Minn.

Buishand, T. A., and Brandsma, T. (2001). "Multisite simulation of daily precipitation and temperature in the Rhine basin by nearest-neighbor resampling." *Water Resour. Res.*, 37(11), 2761–2776.

Clark, M. P., et al. (2004). "A resampling procedure for generating conditioned daily weather sequences." *Water Resour. Res.*, 40, W04304.

El-Rayes, K., and Moselhi, O. (2001). "Impact of rainfall on the productivity of highway construction." *J. Constr. Eng. and Manage.*, 127(2), 125–131.

Hinze, J. (1989). "Weather in construction contracts." *J. Constr. Eng. Manage.*, 115(2), 270–283.

Lall, U., and Sharma, A. (1996). "A nearest neighbor bootstrap for time series resampling." *Water Resour. Res.*, 32(3), 679–693.

National Cooperative Highway Research Program (NCHRP). (1978). "Effect of weather on highway construction." *NCHRP Synthesis 47*, Transportation Research Board, National Research Council, Washington, D.C.

Rajagopalan, B., and Lall, U. (1995). "Seasonality of precipitation along a meridian in the Western U.S." *Geophys. Res. Lett.*, 22(9), 1081–1084.

Rajagopalan, B., and Lall, U. (1999). "A k-nearest-neighbor simulator for daily precipitation and other variables." *Water Resour. Res.*, 35(10), 3089–3101.

Richardson, C. W. (1981). "Stochastic simulation of daily precipitation, temperature, and solar radiation." *Water Resour. Res.*, 17(1), 182–190.

South Dakota DOT (SDDOT). (1997). "Development of working day weather charts for transportation construction in South Dakota." *Final Rep. Study SD97-07*, Rapid City, S.D.

Xi, Y., Rajagopalan, B., and Molenaar, K. R. (2005). "Quantify construction delays due to weather." *Final Rep. of Technology Study*, Dept. of Civil, Environment, and Architecture Engineering, Univ. of Colorado, Boulder, Colo.

Yates, D., Gangopadhyay, S., Rajagopalan, B., and Strzepek, K. (2003). "A technique for generating regional climate scenarios using a nearest-neighbor algorithm." *Water Resour. Res.*, 39(7), 1199–1213.

J. Constr. Eng. Manage., 2010, 136(11): 1160-1168