A CONTROL SYSTEM FRAMEWORK FOR A BRIDGE DECK HEATED BY A GEOTHERMAL HEAT PUMP SYSTEM

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TERMINOLOGY AND NOMENCLATURE

τ	Process time constant
τ_r	Reference Time Constant (for the Smith Predictor and the Dahlin Controller)
τ_I	Integral time constant (for the PID algorithm)
τ_D	Derivative time constant (for the PID algorithm)
α	Time delay
K	Process gain
K_c	Controller gain (for the PID algorithm)
M	Non-dimensional discrete process delay (for the Dahlin Controller algorithm)
D	Non-dimensional discrete process delay (for the Smith Predictor algorithm)
e(t)	Error between the control setpoint and the actual value, as a function of time
g(s)	Process Transfer Function (Laplace Domain)
g(z)	Process Transfer Function (Discrete Domain)
g*(s)	Undelayed Transfer Function (Laplace Domain)
$g_m(s)$	Model Transfer Function (Laplace Domain)
$g_c(s)$	Controller Transfer Function (Laplace Domain)

CMA	Calcium Magnesium Acetate
GCHP	Ground Coupled Heat Pump
GSHP	Ground Source Heat Pump
GWHP	Ground Water Heat Pump
ITAE	Integral of the Time Averaged Error
MIFC	Multiple Independent Feedforward Controller
MBC	Model Based Control
PID	Proportional – Integral – Derivative Controller
RWIS	Road Weather Information System
SWHP	Surface Water Heat Pump
SCWs	Standing Column Well system

CHAPTER I

INTRODUCTION

America's roadways are vital to the health of the U.S. economy. Whether used by trucks for interstate or intrastate commerce, or by commuters on their way to work, the U.S. highway system is the lifeline for business and industry in this country. Therefore, ice and snow accumulation, especially on bridges and overpasses, can cause serious economic and safety concerns to a community. Additionally, bridge deck salting, the prevalent technology available to combat icy bridges, can cause chronic structural degradation problems. One of the solutions becoming available to combat these bridge and overpass icing concerns is geothermal heat pumps [1-8]. These heat pumps can leverage the heat stored underground to circulate a warm fluid through a bridge, thereby raising the bridge deck temperature above freezing.

The work described in this thesis details the first step towards the creation of an autonomous control system to operate a geothermally heated highway bridge. The bridge is being heated to eliminate the harmful and costly effects of ice removal via salting. The development of the control system is a small but integral part of an overall project, nicknamed the Smart Bridge project. The project, funded by grants from the U.S. Department of Transportation's Federal Highway Administration and the State of Oklahoma, is being administered at Oklahoma State University. Representatives from the departments of Mechanical Engineering, Chemical Engineering, Biosystems Engineering, and Civil Engineering, along with members from the Oklahoma Climatological Survey at the University of Oklahoma, are collaborating on the project.

The goal of the Smart Bridge project as a whole is to "Research, design and demonstrate technically feasible, economically acceptable, and environmentally compatible Smart Bridge systems to enhance the nation's highway system safety and reduce its life cycle cost [4]."

This work completes the first of several phases of Smart Bridge control research. The goal for this first phase was to create a base case bridge control system software package that can simulate bridge deck temperature control through use of weather data from the Oklahoma Mesonet weather network and a Fortran-based bridge heat transfer simulation of the Smart Bridge developed by the Oklahoma State University Department of Mechanical Engineering. Therefore, all of the controller software was created in a modular format, with the intention that it would be used as the base for future control developments [9]. Additionally, this work covers the rationale in determining rules for the rule-based weather prediction and control algorithms, basic controller tuning procedures, and a comparison of the performance of several controller algorithms.

The benefits of a control system that can autonomously operate a geothermally heated bridge include:

1) The ability to engage and disengage the heat-pump without manual intervention.
2) Use of available weather data to predict effective heat-pump operating parameters.
3) Room for expansion, such as the inclusion of future adaptive learning algorithms, making the bridge even "smarter."

The justification for the work on the Smart Bridge project is the cost savings that could be realized by the project. The conventional methods of either preventing ice buildup on a bridge (anti-icing) or removing ice (de-icing) from roadways is expensive, as will be shown in Chapter II. Much of that expense comes from the damage that can be done to the bridge structure by anti- or de-icing chemicals. Additional costs incurred are through the purchase and application of the chemicals used. By using a bridge deck heating system, the need for chemicals would be eliminated. The elimination of the chemical-related costs provides a tremendous economic opportunity for bridge deck heating systems, provided the technologies can be built and operated at a reasonable cost.

As a first step towards the evaluation of the cost savings possible from the utilization of a geothermal heat pump-based bridge deck heating system, this thesis will show that a weather-based control system consisting of feedback control system coupled with a weather prediction element is capable of autonomously operating the heating system. It will also be shown that the control system is effective at maintaining the joint goals of minimizing operating costs while ensuring bridge safety.

Thesis Organization

This thesis is organized as follows. The following chapter, Chapter II, will provide a background of the current technologies used for anti-icing and de-icing. Chapter II will also provide background on the fundamentals of ground source heat pumps, as well as background on the type of weather data available for input into the control system. The discussion of the control system is divided into four chapters.

Chapter III describes the weather prediction element of the control system, which utilizes remote weather inputs. A detailed case study of the weather predictor, using actual weather data from the winter of 1997-'98, is included in Chapter IV. The topic of Chapter V is the design of the bridge feedback control system. The results from simulations using the feedback control system are the basis for Chapter VI. The conclusions drawn about the project as a whole are presented in Chapter VII, along with recommendations for future work.

CHAPTER II

BACKGROUND

The United States has over 2.4 million miles of paved roads [10]. In addition, there are over 572,000 bridges in the U.S. roadway inventory [11]. In 1998, nearly three thousand people were killed in vehicular accidents occurring in ice and snow conditions [12]. A study by Marquette University reported by the Salt Institute (SI) has found that de-icing technologies can prevent up to eighty-eight percent of all injury accidents during winter storms, and can pay for itself in as little as the first twenty-five minutes after application [13]. During the winter of 1991-'92, the state of Michigan estimated that they saved $2.5 billion in legal claims alone because of their de-icing efforts [14].

The current standard for bridge deck de-icing is the use of common salt, sodium chloride. However, since the 1970's, highway engineers have known that even the small concentrations of chlorides that seep into the bridge structural rebar components can cause severe maintenance problems and decrease bridge life by up to 20 years [15]. The application of salt to bridges also incurs a significant labor cost. Hence, engineers have been searching for methods to eliminate the safety hazards associated with bridge deck ice buildup, while minimizing the costs associated with the application of salt.

Several technologies exist to handle the problem of bridge deck icing. While it is not a comprehensive list, some of the more common techniques used today are listed in the following sections. The options are divided into technologies that use chemicals applied to the bridge surface, and those technologies that heat a bridge from within.

Salting

Certainly the oldest and most common technique, roadway salting using sodium chloride melts accumulated snow and ice by dissolving into precipitation and depressing the freezing point of the solution. Salting is the most widespread technique because it is relatively cheap. However, the technique's drawbacks include the corrosion of bridges and vehicles, as well as environmental damage to soils and water sources [16, 17].

According to a survey by the Salt Institute [14], municipalities in the U.S. Snow Belt spent between \$895 per mile to \$7575 per mile for winter maintenance. A significant portion of this cost resulted from the application of salt to roadways. In 1997, the Iowa Department of Transportation projccted to use 140,000 tons of salt on their highways. Iowa's total snow removal budget was \$35 million, which covered 11,000 miles of primary and interstate roads in the state [18, 19]. The rock salt alone accounted for \$4.34 million of their budget.

The closest replacement for rock salt that eliminates the harmful chloride-corrosion effects is calcium magnesium acetate (CMA). While the average rock salt price hovers near \$31 per ton, the cost of calcium magnesium acetate is near \$900 per ton, or 28 times more expensive [18]. The U.S. EPA estimates, however, that the direct and indirect costs of salt-related damage to roads, vegetation, and water supplies can approach 15 times the cost to purchase and apply rock salt [17]. While CMA is still not a viable economic alternative to rock salt in general even when the indirect salt costs are included, the difference is much less than it seems by comparing chemical costs alone.

The corrosion caused by rock salt on bridges is due to the small amount of chloride that can seep through porous concrete and attack the metal rebar. This degradation of the bridge structural members causes decreased bridge life, and a reduced approved load rating [17, 20-22]. There have been numerous cases of state transportation departments reducing allowable bridge loads in heavily salted areas after only five years of service, because of structural damage caused by corrosion [11]. The usable life of some bridges has been decreased by 20 years or more because of the problems caused by salting [11].

Researchers have developed several solutions that can reduce the impact of salt on bridge components in recent years. Beginning in earnest in the 1990's, the U.S. Federal Highway Administration (FHWA) began investing in the research of anti-icing technologies [6, 23-25]. While de-icing refers to a procedure that removes precipitation that has already bonded to a road surface, anti-icing projects attempt to eliminate precipitation from bonding to the roadway in the first place. The use of salt-trucks after a storm enters an area is an example of de-icing. Many departments of transportation are now, however, applying aqueous layers of salt, among other solutions, on bridges before a winter storm hits an area [12, 26, 27]. To be effective, these anti-icing solutions must be applied between thirty-minutes and two-hours prior to a precipitation event [25]. This leads to the need for Road Weather Information Systems, which is discussed in a later section.

Heavy use of rock salt for de-icing or anti-icing can cause serious environmental impacts, particularly to soils and groundwater. Studies conducted in Ontario, Canada, indicate that 45% of rock salt applied to roads runs off and is absorbed in a benign manner [17]. According to the Canadian study, the balance contaminates local shallow aquifers. While the allowable level of chloride in drinking water by both the U.S. EPA and the Canadian government is 250 mg/L, levels as high as 14,000 mg/L have been identified in aquifers adjacent to major highways in the city of Toronto [17]. Additionally, high concentrations of sodium can be toxic to plants, and harmful to soils.

Non-Corrosive Chemicals

While sodium chloride salt is the most commonly used compound for roadway de-icing, other options are available. Calcium magnesium acetate was mentioned in the previous section, but it is only one of the available solutions. Table 2.1 lists a few options, along with their benefits and drawbacks [17, 22, 25, 28-31]. None of these additional chemical options can compete with the \$31 per ton average sodium chloride price. Even when the environmental and structural effects of rock salt are factored into the purchase price (\$465 per ton, estimated at 15x the purchased price) [17], sodium chloride still is cheaper on a per ton basis than all the alternatives in Table 2.1. Therefore, this price disparity has led to the investigation of non-chemical methods of ice prevention, which are discussed in the following section.

Bridge Deck Heating Systems

Active bridge deck heating systems are an alternative to the application of salts and chemicals [4, 5, 7, 8, 32-45]. The primary advantage of these types of systems is their automatic nature. Assuming that the system is outfitted with either an effective control system or a method for remote activation, active heating systems can eliminate the equipment and manpower costs and delays associated with salting. This automatic nature is particularly useful in very remote bridge locations, as well as high-traffic areas.

Table 2.1 - Alternatives to Sodium Chloride

Chemical	*Cost*	*Benefits*	*Disadvantages*
Sodium Chloride	\$31/ton \$9.7E-31 / ion	Cheap, effective	Chloride corrosion, ecological contamination
Calcium Chloride	\$250 / ton \$2.1E-30 / ion	More effective than NaCl at low temperature; hygroscopic so stays on road longer	Same problem of chloride contamination and corrosion as NaCl; High Cost
Calcium Magnesium Acetate	\$900 / ton \$1.4E-30 / ion	Low environmental impact	High Cost Can cause algae in small ponds; Slightly less effective than NaCl
Magnesium Chloride	\$260 / ton \$2.5E-30 / ion	Hygroscopic so stays on road longer than NaCl	Same environmental problem of chloride contamination and corrosion as NaCl; High Cost
Potassium Acetate	\$2000 / ton \$3.7E-29 / ion	Low corrosion, low environmental impact. Base of several commercial chlorine-free de-icing products	High cost
Potassium Chloride	\$105 / ton \$2.6E-30 / ion	More effective than NaCl at low temperatures; hygroscopic so stays on road longer than NaCl	Same problem of chloride contamination and corrosion as NaCl; High Cost
Urea	\$85 / ton \$2.6E-30 / ion	Less corrosive than NaCl; Lessened environmental impact	Can cause algae growth in ponds
Sodium Salts of Carboxylic Acids	\$\$\$	Similar effectiveness as NaCl Reduces environmental impact resulting from chlorides	Same environmental problem of sodium contamination; Under development – not widely available

Most bridge deck heating systems can be compared to the common, household water heater. Essentially, the system circulates a mixture of water and antifreeze solution through an industrial-sized water heater. The heat from the water and antifreeze solution is then exchanged with a separate fluid that is sent through an array of pipes buried shallowly underneath the road surface to maintain a roadbed temperature above freezing, as is shown on the bridge depicted in Figure 2.1. The predominant difference between the different heating systems lies in the heating element.

The major types of active bridge deck heating systems are compared and contrasted in the following sections.

Electric Heating Systems. While a large percentage of home water heating systems utilize an electric heating element, this is not the case with bridge deck systems. Very few of the heated bridges referred to in the open literature use electric heating elements because of high operating costs [5, 7, 8, 32, 35-38, 41, 43, 46-48]. In fact, electric resistance heat is among the most inefficient means of heating. According to the U.S. Department of Energy, electric resistance heating is on the order of 50 percent less efficient than equivalent geothermal heat pump systems [1].

Fuel Gas Heating. As in home water heating systems, fuel gas (natural gas, propane, etc.) is a viable option for bridge deck heating systems. The most prominent example of the utilization of gas heating is the Route 60 Bridge in Amherst County, Virginia [32, 43, 49]. A joint project between the Virginia Department of Transportation and the Federal Highway Administration, the Route 60 Bridge uses a propane furnace to heat the antifreeze solution, which then exchanges with a separate bridge deck heating fluid.

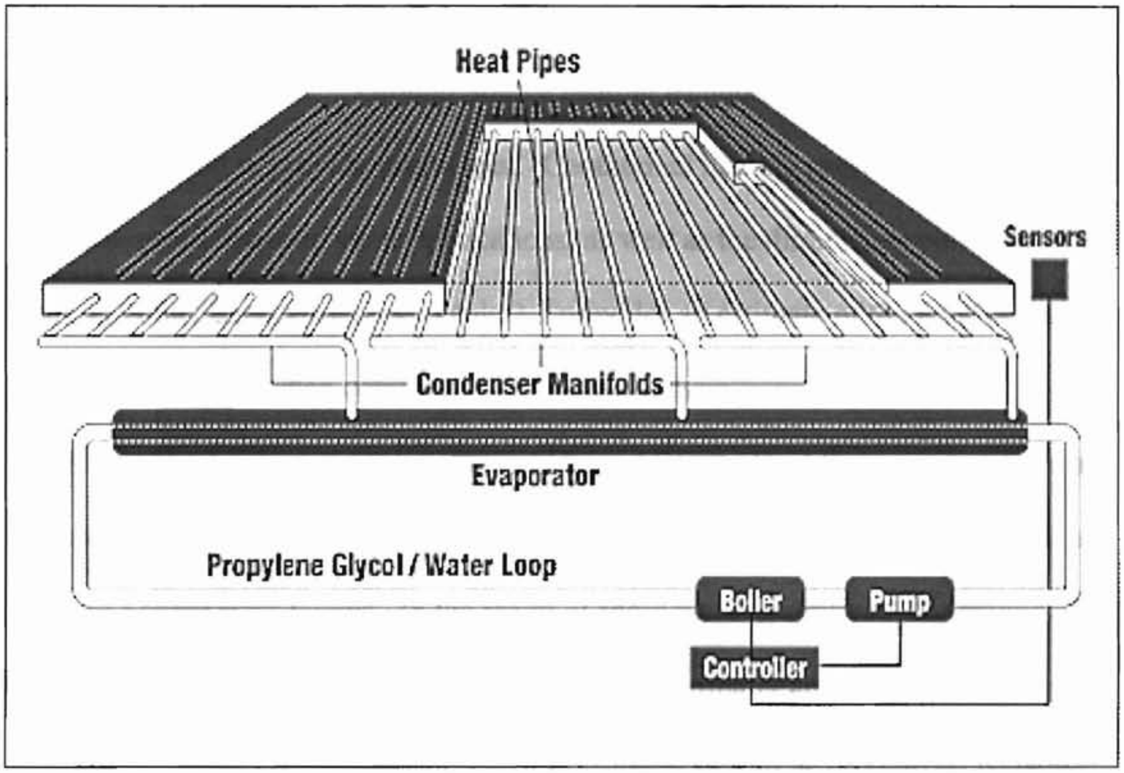


Figure 2.1 – Route 60 Bridge [43]

Figure 2.2 outlines the simple control algorithm used to operate the bridge. The Route 60 Bridge utilizes a self-contained road weather information system to track bridge surface temperatures and precipitation rates [43]. This information is then used to determine when to operate the bridge heating system.

Ground Source Heating. Ground Source heating technologies leverage the energy stored in the ground to provide useful heat. Geothermal heating sources are attractive due to the cost efficiency in some applications, as well as the diminished pollution when compared to other energy sources. Table 2.2 provides an estimate of the relative cost of ground source heating when compared to other methods.

A wealth of potential applications of Ground Source Heat Pumps is available in the literature [2, 7, 32, 35, 37]. In the U.S., home heating and cooling is the primary use for Ground Source Heat Pumps. In the realm of snow melting applications, ground source heat pumps have been used extensively in geothermally active areas as pavement heating systems. The city of Klamath Falls, in Oregon, as well as Reykjavik, Iceland, have successfully used pavement heating systems for many years.

Ground Source Heat Pumps (GSHPs) can be configured in a number of ways. The four most common configurations are Ground Water Heat Pump Systems (GWHPs), Ground Coupled Heat Pump Systems (GCHPs), Surface Water Heat Pump Systems (SWHPs), and Standing Column Well Systems (SCWs) [2]. Ground Water Heat Pumps exchange the heated fluid directly with the groundwater. Ground Coupled Heat Pumps exchange heat with the ground through heat transfer tubes placed in the ground. Surface Water Heat Pumps use the thermal reservoir available in ponds and lakes, while Standing Column Well Systems simply use a well drilled deep into the ground to exchange heat

Any of three conditions can activate the system:

- Deck surface sensor indicates snow or ice
- Precipitation sensor indicates precipitation and deck surface temperature is below 35 degrees Fahrenheit
- Deck surface sensor indicates wet deck and the surface temperature is below 35 degrees Fahrenheit

Either of two conditions will shut off the system:

- Deck surface sensor has indicated clear surface for more than 10 minutes
- Deck surface temperature is above 40 degrees Fahrenheit

Figure 2.2 - Route 60 Bridge Control Algorithm

Table 2.2 - Heating Source Operating Cost Comparisons

Heating Source	*Cost Basis*	*Estimated $/MMBTU*
Propane	$1.20 / gal.	15.86
Natural Gas	$0.60 / therm	7.14
Electric Resistance	$0.07 / kWh	20.51
Ground-Source Heat Pump*	$0.07 / kWh	5.86

***ASSUMES A 3.5 COEFFICIENT OF PERFORMANCE**

between the ground and the heat transfer fluid. Since this project requires the use of an anti-freeze solution (42% propylene glycol, 58% water), good environmental stewardship dictates that a closed system is used so as not to contaminate any ecological systems. Therefore, the rest of this work focuses on the development of Ground Coupled Heat Pump Systems (GCHPs).

Ground Coupled Heat Pump Systems (GCHPs). Ground Coupled Heat Pump systems are configured to recover heat from the ground by circulating a fluid through pipes located in underground boreholes (see Figure 2.3). The benefit of GCHPs is that, since the heat transfer fluid is circulated through pipes, the approach avoids the potential for ground water contamination that is inherent in open systems.

Ground coupled heat pump systems may be oriented either vertically or horizontally. Horizontal applications generally consist of a large field of straight tubes buried between 3 and 6 feet underground. Vertical arrangements generally take up significantly less surface area, but can be 250 or more feet deep. Consequently, vertical systems cost more to install, yet they require the use of much less physical land area. Additionally, performance of horizontal systems fluctuates more due to ambient conditions because of the shallow depths used. Therefore, most industrial applications use vertical designs because of the large heat transfer area required. Figure 2.4 shows a typical GCHP system used as a bridge deck anti-icing system. The system consists of three sections: the ground loop, the heat pump, and the bridge deck piping.

The ground loop is essentially a system of U-tube heat exchangers located in bore holes as deep as 250 feet in the ground. The fluid circulated through the ground loop is

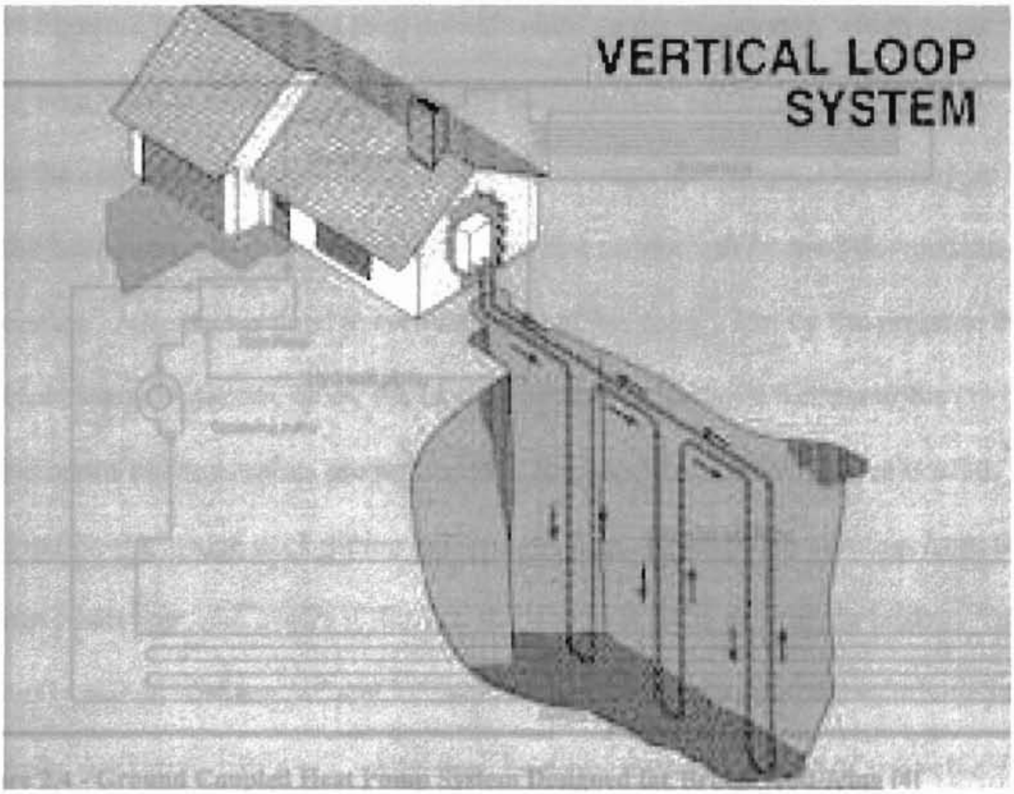


Figure 2.3 - Vertical Ground Coupled Heat Pump System (Courtesy of the International Ground Source Heat Pump Association)

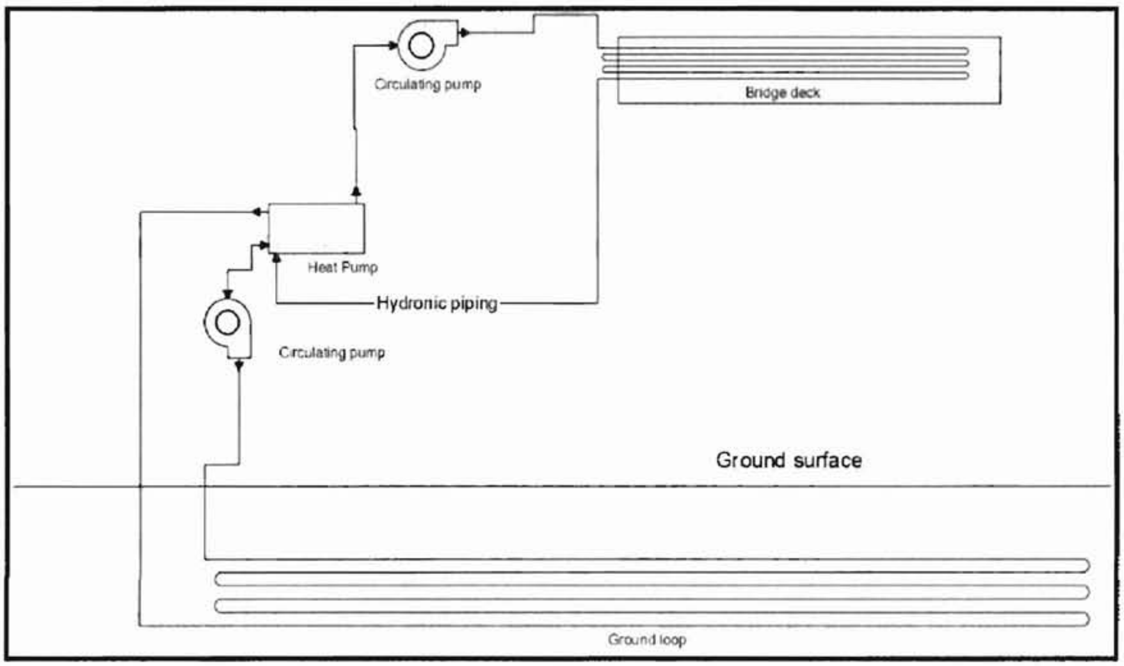


Figure 2.4 - Ground Coupled Heat Pump System Designed for Bridge Anti-Icing [4]

usually an antifreeze solution of propylene glycol and water, and provides a heat source for the heat pump. Ground loop temperatures vary primarily based on usage, geographical region, and type of soil.

The heat pump is simply a modification on the standard refrigeration cycle, as shown in Figure 2.5. The ground loop provides heat to the evaporator, which evaporates the refrigerant used in the heat pump cycle. The condenser acts as a heat source, warming the anti-freeze solution being circulated through the bridge. Depending on the size of the heat pump, either an expansion valve or a turbine can be used downstream of the condenser. A turbine is used to recover some of the energy lost by the pressure drop. However, in many instances, either the capital required to install a turbine or the additional operating constraints are prohibitive, so a simple expansion valve is used.

Finally, the bridge deck piping delivers the heated anti-freeze solution from the heat pump condenser, and cycles it through the bridge in order to heat the bridge. Tubes are normally placed between ¼" and ¾" inch below the roadway surface to minimize the heat transfer dynamics, while still protecting the tubes from the weight of the vehicles.

Road Weather Information Systems (RWIS)

This thesis centers on the investigation of the controllability of a geothermally heated bridge using input from remote weather stations. This control problem is unique because of the relatively few similar systems available for comparison [50-62]. Also, due to the lead-time needed to warm a bridge deck, weather forecasting has been an essential element in developing the control algorithm [39, 49, 63-79]. Therefore, this control

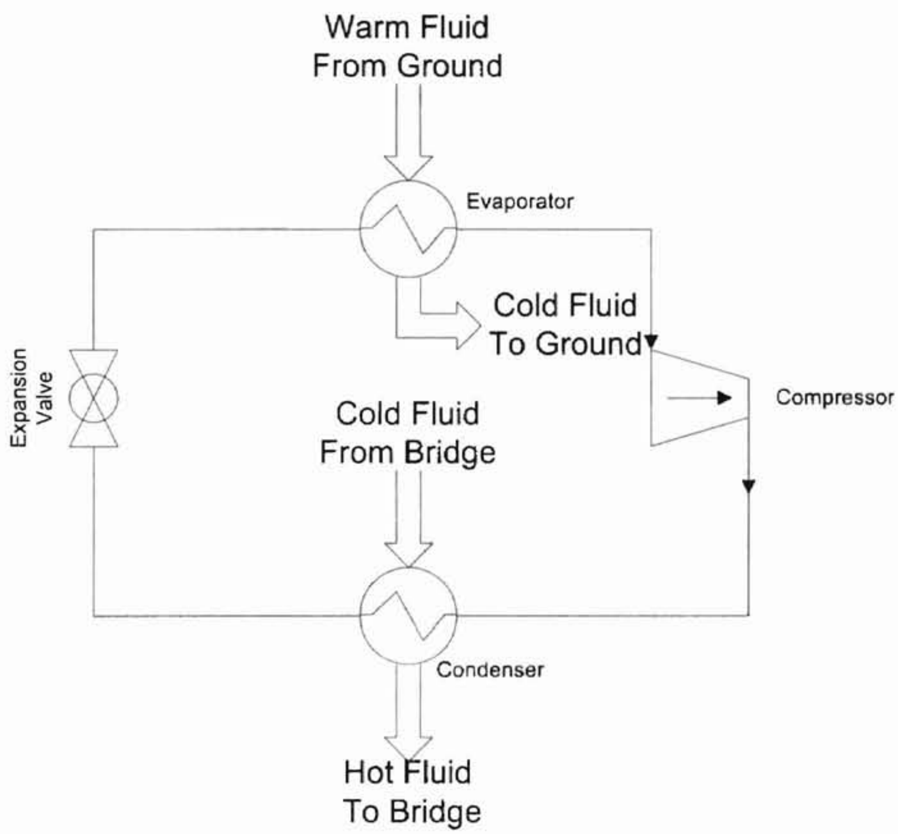


Figure 2.5 - Bridge Heat Pump Diagram

problem has provided a unique opportunity to merge the field of process control with meteorology.

Over the past 10 years, Road Weather Information Systems (RWISs) have been installed by most states where roadway icing is a concern [24]. European countries, particularly Denmark and the United Kingdom, have been equally interested in installing RWIS systems [60]. The intent for these systems is to allow roadway maintenance departments access to current weather and roadway conditions so, in situations where ice or snow is possible, they can either dispatch road crews or activate automatic road management systems, like heated bridges.

One of the most sophisticated RWIS systems is run by the Danish Meteorological Institute (DMI) [60]. The Danish system utilizes over 200 remote road weather stations throughout the country. A list of the monitored variables in the Danish system is shown in Table 2.3. The Danish model uses this monitored data to predict conditions such as ambient temperature, road bed temperature, precipitation, humidity, and wind speed and direction for each of the remote stations. This is done by utilizing the Danish Road Conditions Model (RCM) in conjunction with the High Resolution Limited Area Model, maintained by the DMI [71].

While the DMI has had success with the roadbed monitoring system, the system still exhibits some difficulties. Notably, the system is unable to attain a reliable prediction resolution under 10 km^2 [60, 61]. This resolution limit is primarily due to two factors. First, the system is limited to a 10-minute weather condition update frequency. The 10-minute period is enough time for a storm to either change direction or speed drastically, therefore decreasing accuracy. Secondly, the Danish system is limited by the

Table 2.3 - Danish Meteorological Institute Measured RWIS Variables

• Temperature at 2-meter height	• Fractional Cloud Cover
• Specific Humidity at 2-meter height	• Cloud Height
• Surface Pressure	• Road Surface Temperature
• Wind Speed at 10-meter height	• Road Service Water Level
• Precipitation Intensity	• Road Surface Ice Accumulation
• Dewpoint at 2-meter height	• Vertical Road Temperature Profile

system's ability to model cloud size and intensity, as well as the dynamic behavior of a cloud's features. This limitation decreases the accuracy of precipitation prediction in a given storm system.

Many US states are now using RWIS systems, primarily to determine where and when they should dispatch road crews to a potential storm location [18, 23, 50, 53, 69, 75, 80-83]. The US Department of Transportation, under the Strategic Highway Research Program as well as other similar programs, has promoted projects in many snow belt states [84]. These programs have been developed mainly to reduce the manpower expense of sending crews to remote areas to watch and wait for storms that may come through the area. The Colorado DOT has used RWIS's since the mid-1980's, and have since expanded the network to 48 stations statewide [85]. By utilizing the RWIS, the Colorado DOT has been able to minimize the use of harmful anti-icing chemicals, while also reducing the labor costs associated with the application of these chemicals. In Massachusetts, where a similar RWIS program is in place, the state Highway Department estimates that the statewide system of weather stations could save up to $200,000 per year in the maintenance budget [86].

The Oklahoma Mesonet. The Oklahoma Mesonet is a system of 114 remote weather stations that continuously measure a variety of weather data for use by state meteorologists, agriculturists, and planners throughout the state [87]. The name "Mesonet" is derived from the meteorological term "mesoscale," which essentially refers to weather features on a resolution of between a few square kilometers to a few hundred square kilometers [87]. Tornadoes, thunderstorms, and squall lines are examples of mesoscale phenomenon.

A sample of the types of variables measured by the Mesonet are listed in Figure 2.6. Every fifteen minutes, each weather station transmits data to the central computers of the Oklahoma Climatological Survey (OCS) via radio over the Oklahoma Law Enforcement Telecommunications System (OLETS). A picture of a typical Mesonet weather station is shown in Figure 2.7.

With at least one weather site in each of Oklahoma's 77 counties, the Oklahoma Mesonet has been utilized by the Oklahoma Department of Transportation (ODOT). While other states were struggling to build RWIS systems, Oklahoma transportation planners discovered they essentially had a large RWIS system already in operation in the state. With this Mesonet data, the ODOT has already begun to plan which roads to ice and sand during potentially freezing conditions. Another current application involves using ambient temperature and humidity data to determine which roads are dry enough to paint on any particular day.

National Weather Service. In the state of Oklahoma, the National Weather Service (NWS) operates 14 automated weather stations, which are capable of measuring and transmitting weather data once each hour [88]. Because of the decreased resolution caused by the time lag in data and the limited number of weather stations, the National Weather Service system is unable to provide the in-state data needed to provide as detailed a forecast as could be obtained with the Mesonet system. However, by utilizing the NWS system to monitor weather systems coming into the state, and cross-validating

Oklahoma Mesonet
Measured Variables

Standard Measurments

Air temperature at 1.5 meters above ground
Relative humidity at 1.5 meters above ground
Wind speed and direction 10 meters above ground
Barometric pressure
Rainfall
Solar radiation
Soil temperature at 10 centimeters below ground

Other measurements
(available at many stations)

Air temperature at 9 meters above ground
Wind speed at 2 meters above ground
Leaf wetness
Soil moisture 5, 25, 60, and 75 centimeters
Soil temperature at 4 and 30 centimeters

All data except leaf moisture is available in 5 minute averages, reported every 15 minutes. Leaf moisture data consists of a single 15 minute average.

Figure 2.6 - Oklahoma Mesonet Measured Variables

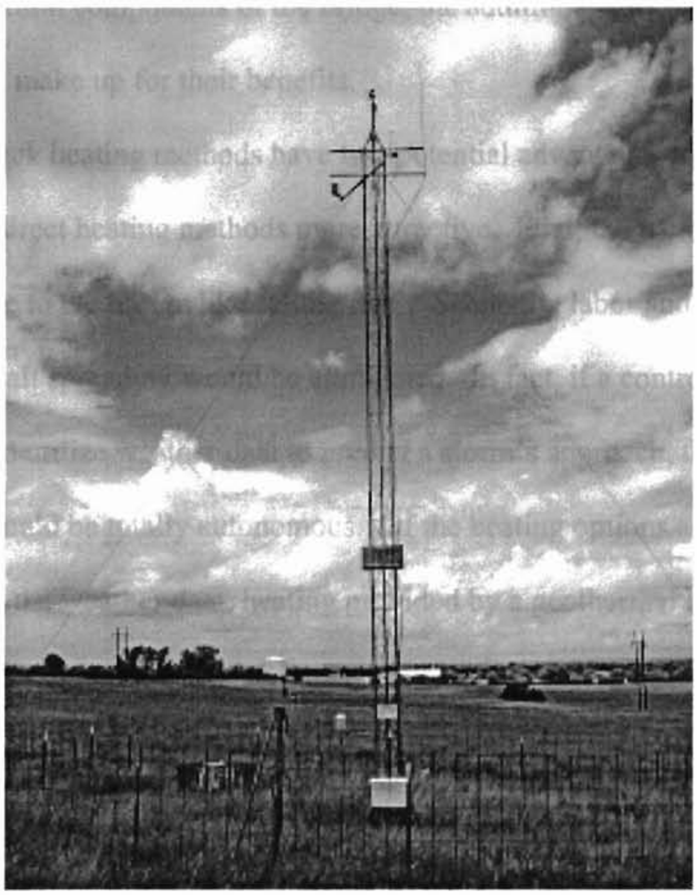


Figure 2.7 – Woodward, Oklahoma Mesonet Station

data from both systems inside the state, weather forecasters are able to forecast fronts in the state with mesoscale accuracy.

Conclusion

Several alternatives are available to combat the drawback of using rock salt as the primary bridge de-icing agent. While other chemicals are available that do not corrode the structural components of the bridge, the additional cost of the replacement chemicals do not make up for their benefits.

Bridge deck heating methods have two potential advantages over salting that could make the direct heating methods more attractive. First, the methods do not cause structural damage to the bridge like salting does. Secondly, labor and material costs associated with salt spreading would be eliminated. In fact, if a control system could be created that could utilize weather data to predict a storm's approach, the bridge deck heating system could be totally autonomous. Of the heating options available for use in conjunction with the weather data, heating provided by a geothermal heat pump is the cheapest per BTU to operate. Capital costs, while vital to the evaluation of heating systems, are beyond the scope of this work.

Since all of the components to create a control system for a heat-pump assisted bridge are available, as explained throughout this chapter, the parts need only to be integrated. Integrating these individual control components and providing an autonomous, efficient geothermal heat pump driven bridge deck heating system is the goal of the following chapters of this thesis.

CHAPTER III

CONTROL OF A GEOTHERMALLY-HEATED BRIDGE USING WEATHER PREDICTORS

The goal of this project is to describe and simulate a control system that would be the basis for the system used to control a geothermally-heated bridge. The goal in this initial work is to prove that the automated control system can outperform a similar bridge operated manually by transportation officials. The control system can be broken down into two separate parts. The first component in the system is the weather predictor, which is detailed below. The general feedback controller is discussed in Chapter V.

The performance criteria for the weather predictor component of the control system are threefold. First, the weather predictor system must be effective at predicting freezing air temperatures with enough time for a given bridge to respond and heat the bridge deck to above freezing. Secondly, the control system should be efficient. This means that the controller should minimize the total amount of operating time, without sacrificing bridge safety, or effectiveness. Finally, the weather prediction component needs to be versatile, allowing for ease of installation in different areas of the country. However, before analyzing the performance of the weather predictor component, a detailed description of the design and development of the predictor is given in the following section.

Weather Prediction Component Design

The bridge control system was designed and developed using the LabView 5.1.1 software by National Instruments [89]. The software was used to create a PC-based weather prediction component that can interact with both a simulated bridge model, as well as plug into the real bridge when it becomes available.

Several challenges existed before a weather predictor could be realized. First, a mechanism to retrieve and interpret weather data needed to be developed. Secondly, since an actual geo-thermally heated bridge is not yet ready to be tested, a method had to be developed to allow the control simulation to interact with a Fortran-77 based bridge simulation. Finally, an evaluation program needed to be created to allow for the testing of the weather prediction algorithm.

Weather Data Manipulation

The bridge weather predictor utilizes weather data available from the Oklahoma Mesonet. However, the software is also capable of utilizing data from the National Weather Service, in addition to Road Weather Information Systems, and other private weather sources. Mesonet data was used for this project because of the increased quantity and frequency of data available. For the purpose of this research, the bridge is assumed to be located in Woodward, Oklahoma. This site was chosen because of the quantity and variety of winter weather common to this region, in addition to the fact that a Mesonet station is located only a few hundred feet from the National Weather Service station for the northwest part of the state. This proximity allows for easy correlation and comparison of data between the NWS and the Mesonet.

The weather data is being used for two distinct purposes. First, the Fortran-77 based bridge simulation, developed in a program called HVACSIM+, requires weather data to calculate the dynamic response of a geo-thermally heated bridge under different operating and weather conditions. The data required is shown in Table 3.1. Secondly, weather data is used by the weather predictor to determine when the bridge heat pump needs to begin preheating the bridge in preparation of imminent severe weather.

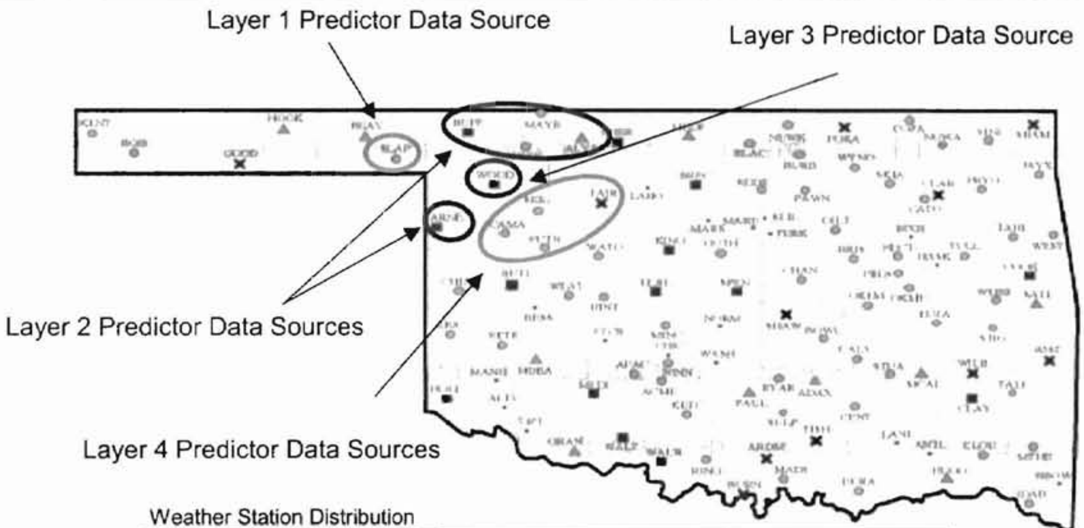
Automated delivery of Mesonet weather data will be achieved via the Internet by FTP. Each weather station in the Mesonet network collects and relays data to the central computers of the Oklahoma Climatological Survey every 15 minutes. This data is then processed, and saved in a text-based format. The LabView based PC-Control software is able to download the data, and read current conditions from weather sites determined to be pertinent to forecasting the future conditions at the bridge site.

The first challenge in configuring the weather data program is to determine the number and location of weather stations needed to obtain an accurate picture of incoming storms. In Oklahoma, many cold-weather fronts enter the state through the panhandle in the northwest part of the state. Therefore, it was determined that the weather prediction component of the control system should utilize data from weather stations roughly oriented on a line from Woodward pointing northwest (see Figure 3.1). This orientation would catch a majority of winter weather patterns. However, because the direction of travel of cold fronts is not always predictable, data from several other weather stations circling the bridge site are used to catch anomalies.

A total of ten weather stations are being utilized for the present weather predictor. In addition to providing current weather information to the bridge simulation, the data is

Table 3.1 - Weather Data Required by HVACSIM+ Model

Required Model Weather Data	
Ambient Temperature (°C)	Sky Temperature (°C)
Rainfall (mm/hr)	Snowfall (mm/hr water equivalent)
Wind Speed (m/s)	Wind Direction (Degrees from North)
Relative Humidity (%)	Solar Radiation (kW/m^2)
Solar Angle of Incidence (Degrees)	



Weather Station Distribution

Layer 1	Slapout			
Layer 2	Buffalo	Alva	May Ranch	Arnett
Layer 3	Woodward			
Layer 4	Putnam	Fairview	Camargo	

Figure 3.1 – Weather Station Utilization

being used to generate a rough short-term weather forecast. Currently, prediction is done by linear extrapolation using current and past data. Ambient temperature is the only forecasted value that is currently being used by the weather predictor. Precipitation forecasting is an obvious choice for utilization in the control system, as well. However, the Mesonet is only able to measure liquid precipitation. Ice, snow, and hail simply build up in the instrument, and register only when precipitation melts, sometimes hours or even days later. Work is currently ongoing on developing a radar-based short-term precipitation forecasting system that would overcome the current shortcomings.

Multiple Independent Predictors

Once all of the weather data is sampled and transfered into the LabView database, the challenge then becomes determining how to create an automated framework capable of interpreting the data and making control judgements based on the sometimes conflicting information. In order to address this problem, a unique system was devised, termed Multiple Independent Predictors (MIPs).

The concept behind MIPs is simple. Pieces of weather data retrieved and stored in the LabView database are grouped based on the best judgement of the control engineers and meteorologists into independent controllers that each makes a short-term forecast. For instance, temperature is the primary forecasted variable in the current version of the control software. Since it is known that most cold weather comes from the northwest in Oklahoma, a group of temperature forecasting predictors are created to generate a picture of the speed and direction of temperature changes in fronts approaching Woodward, Oklahoma. Figure 3.1 illustrates this idea.

The data gathered by each predictor is then interpreted based upon a system of user-configurable rules. An example of a rule set is listed in Table 3.2. These rules are to be considered as the default rule set in this thesis, and will be used for all simulations except where specified otherwise. The rule set is intended to utilize the current weather data and trends at the weather site. If conditions at the remote site are perceived as indicating a possible cold weather storm that is moving towards the bridge site, a warning will be issued by the LabView control software. If a sufficient number of weather sites indicate a warning, then the geothermal bridge deck heating system will be turned on, and will begin preheating. Once the bridge heater is turned on, the feedback control system (detailed in Chapter V) manipulates bridge flow rates to maintain the bridge deck temperature setpoint. The feedback loop is constrained by a minimum flowrate through the bridge, regardless of average bridge deck temperature, to ensure that the controller could quickly respond to any cold weather front indicated by the MIPs.

Predictor Versatility

The MIP framework is versatile enough to be used in many different areas of the country. The requirements for an easy installation of the system are threefold. The required components are the availability of weather station data, a weather station communication system, and the capability to produce and decode weather station data files.

First, an area must be covered by a system of remote weather stations, sufficient enough to provide data on upcoming storms coming from any direction. The required

Table 3.2 - Default Weather Predictor Rule Set

Controller Layer Warning Conditions	Bridge Preheat Conditions
If the ambient temperature of any weather station in a layer is below the layer's approach temperature, then issue a WARNING.	If the # of WARNINGS for any layer is greater than the *layer threshold*, then PREHEAT.
If the slope of the ambient temperature of any weather station in a layer forecasts the temperature to drop below the layer *approach temperature* within the layer's *warn time*, issue a WARNING.	If the bridge was operating during the last iteration, and has been running for less that the *bridge hold time*, then PREHEAT.
Mesonet, for instance, is transmitted to the Okla 15 minutes over the Oklahoma Law Enforcemen	If bridge site (Layer 3) temperature is 8 *danger temperature*, then PREHEAT.

number of stations will vary based primarily on terrain and geographical location. For instance, a bridge located in a mountainous area of Colorado would likely need many more stations than a bridge located along a flat stretch of southern Oklahoma. The number of controllers, or layers, also can dictate the amount of forewarning available for fast moving storms. The more weather stations available in an area can lead to more layers being defined further away from the bridge site, which leads to more accurate short term forecasting. The current software allows for up to four layers, but is upgradeable via minor programming modifications.

The communication method used is also an important consideration when deciding whether this MIP system is a match for a given area. Since up-to-the-minute data is crucial, the remote weather stations used must be able to transmit data to a central data gathering system in a timely manner. Updated weather data from the Oklahoma Mesonet, for instance, is transmitted to the Oklahoma Climatological Survey office every 15 minutes over the Oklahoma Law Enforcement Telecommunication System (OLETS). Text file tabulations of the data is then available to the control system by setting up an FTP (File Transfer Protocol) connection with the OCS computers. As the frequency of updates decreases, the effectiveness and the efficiency of the predictor will suffer. Typical data from National Weather Service sites is available once per hour. Because of this decreased frequency of data, the weather stations utilized would need to be spaced further away from the bridge site in order to provide sufficient warning of approaching cold weather.

Finally, in order for this predictor to work in an area, the data provided to the control system must be in a data format that the program can interpret. The current system can decode data in most delimited, text-based file formats with little or no program modifications. Utilization of more sophisticated binary or non-delimited text based formats would require a more extensive program modification.

User-Adjusted Parameters

Several user adjustable parameters are needed to make the MIP rule-based system flexible. The five parameters are the danger temperature, the bridge response time, the approach temperature, the warn time, and the controller threshold. The form and function of each of these parameters is detailed below.

Danger Temperature. The danger temperature is defined as the ambient temperature, measured at the bridge site, at which the bridge heating system will always be required to begin heating the bridge. At or below the danger temperature, the bridge heating system must always be operating, regardless of data available from any of the remote weather stations. The default danger temperature for the Woodward bridge site is 0.0 ^{o}C.

Bridge Response Time. The bridge response time is the estimated maximum length of time that the bridge deck heating system would need be operating to ensure that the average bridge deck temperature could be held at 33.5 ^{o}F. The feedback control system simulation uses this parameter to calculate the effectiveness of the control system. If the ambient temperature at the bridge site drops below freezing, the LabView simulation calculates whether the bridge deck was successfully preheated prior to the freezing conditions. If the weather predictor has been signaling to heat the bridge for a period of time greater than or equal to the bridge response time, then the control system classifies the performance as efficient, because the potential for bridge deck icing was prevented. However, if the bridge had been heating for a period of time less than the bridge response time, then the performance was not efficient, because there would have been a potential of ice formation on the bridge.

Approach Temperature. The approach temperature is the ambient temperature at which a cold-weather warning would be issued for any of the remote weather stations monitored by each of the predictor layers. For instance, every station in the Layer 2 predictor illustrated in Figure 3.1 has an approach temperature of $-1.5\ ^{o}C$. Therefore, whenever the ambient temperature of the weather stations in the layer drop to below $-1.5\ ^{o}C$, a warning is issued. The warning remains active until the temperature at the layer rises above the approach temperature.

Warn Time. The warn time is the length of time that the weather predictor for each layer calculates a forecast. A rule in the algorithm then compares the forecasted temperatures with the approach temperature for the layer. If the forecast predicts that the ambient temperature at a weather station will drop below the approach temperature within the warn time, then a warning is issued. The larger the value of the warn time, the longer the weather forecast window. As the warn time is decreased, the forecast becomes more short-term. Since the forecast is calculated linearly based on the slope of the short-term temperature history, a longer warn time would mean that the predictor algorithm would become more conservative. Therefore, increasing the warn time would generally allow the bridge more preheating time prior to an impending cold weather front.

Layer Threshold. It is common for a particular weather predictor layer to have multiple weather stations. Layer 2 from Figure 3.1 contains five weather stations. Occasionally, an instrument on a station becomes damaged or is otherwise unavailable. During other situations, an instrument might have drifted from its calibration, thus reporting erroneous data. For these reasons, the layer threshold is a parameter used by the rule-based algorithm that limits a controller from switching on the heating system until a defined number of warning conditions are reported. Layer 4, for instance, requires that two warnings are issued before the bridge is turned on.

Bridge Hold Time. The bridge hold time is the amount of time that the bridge deck heating system must remain on after being started. This parameter helps to ensure that the heating system isn't constantly being turned on and off, which could cause unnecessary wear on the mechanical system components, such as the heat pump compressor. The default bridge hold time is set at 44 minutes. The time of 44 minutes was chosen because that would allow the bridge to be switched off after 45 minutes of operation, since the time step used by the weather predictor is 15 minutes, corresponding to the weather data update frequency.

Conclusion

The key to MIPs is that any predictor that indicates an impending storm can turn on the bridge preheating system. Conversely, all predictors must indicate acceptable weather forecasts in order for the bridge deck heating to be turned off. The conservative nature of this system helps to ensure that the bridge remains ice-free, while still reducing unnecessary operating costs.

CHAPTER IV

MULTIPLE INDEPENDENT PREDICTOR CASE STUDY

In order to test the performance of the Multiple Independent Predictors, a simulation was performed using Oklahoma Mesonet data from the winter of 1997-98 for a bridge site assumed to be located in Woodward, Oklahoma. The following sections provide a detailed description of the assumptions used during the simulation, along with the numerical values of all of the parameters used. Results, as well as the conclusions drawn from the simulation are also presented.

Assumptions

Since simulation was performed using an imaginary bridge site location in Northwestern Oklahoma, and utilized discrete, archived weather data, some assumptions were necessary. The required assumptions are listed below.

Warming Requirements. The first assumption was that in order to be considered ice-free, the bridge deck surface needed to be warmed to an average bridge deck temperature of 33.5 °F whenever the weather station closest to the bridge site indicated an ambient temperature less than or equal to 0 °C. This assumption is necessary because Mesonet weather stations are unable to accurately measure freezing precipitation. Since any precipitation on the bridge surface can cause an icy condition, this assumption was necessary to ensure that the bridge remained ice free during freezing precipitation events.

Bridge Site Weather Conditions. The weather conditions at the bridge site are assumed to be the same as those reported by the closest weather station. In this simulation, this assumption means that data from the Woodward Mesonet site is assumed to be the conditions found at the hypothetical Woodward Smart Bridge site. The main weather variable that might consistently be different than the data reported by the weather station is relative humidity. Significant relative humidity differences could exist if the bridge spans a body of water, such as a river or a pond, when the corresponding weather site was located far from water. If the actual bridge site relative humidity were greater than the value reported by the weather station, the required preheat time returned from the bridge simulation and used for the bridge response time parameter would likely be underestimated.

Weather Dynamics. The weather conditions at each weather station, and at the bridge site, are assumed to be held constant in the period of time between the 15 minute weather updates available from the Oklahoma Mesonet. This assumption, over the course of a winter, probably does not cause significant error in the total bridge operating time, because the underestimation of the weather conditions in one instance likely makes up for an overestimation during another instance.

Heat Pump Sizing. This simulation assumes that the bridge deck heating system is sized such that it can heat the bridge deck to 33.5 $^{\circ}$C under any possible weather conditions seen in Woodward, Oklahoma.

The preheat time required for even the severest of conditions is assumed to be less than or equal to the value of the user-adjustable bridge response time parameter. This assumption is necessary due to the limitations of the HCAVSIM+ based bridge model. The bridge model currently utilizes a single heat pump. The actual bridge deck heating system, when constructed, will utilize multiple heat pumps running in either serial or parallel arrangements. Multiple heat pumps are needed because of the limited operating range of a single heat pump due to mechanical constraints imposed by the heat pump cycle. While adding the ability to model multiple heat pumps in a variety of flow arrangements is to be included in future versions of the bridge model, its absence requires that the bridge response time be selected by utilizing both the model and good judgement.

User-Adjustable Parameter Values. The MIP parameters described in detail in the previous chapter and used for the simulation are listed in Figures 4.1 and Table 4.1. Figure 4.1 is an actual screenshot from the LabView control software. Table 4.1 also lists the parameters, along with a map of the predictor layers used. Figure 4.2 shows the general layout of the LabView software components, showing the modular structure that will allow easier installation and integration with future "smart" bridge applications. Additional information about the development of the bridge software can be found in a technical report [9].

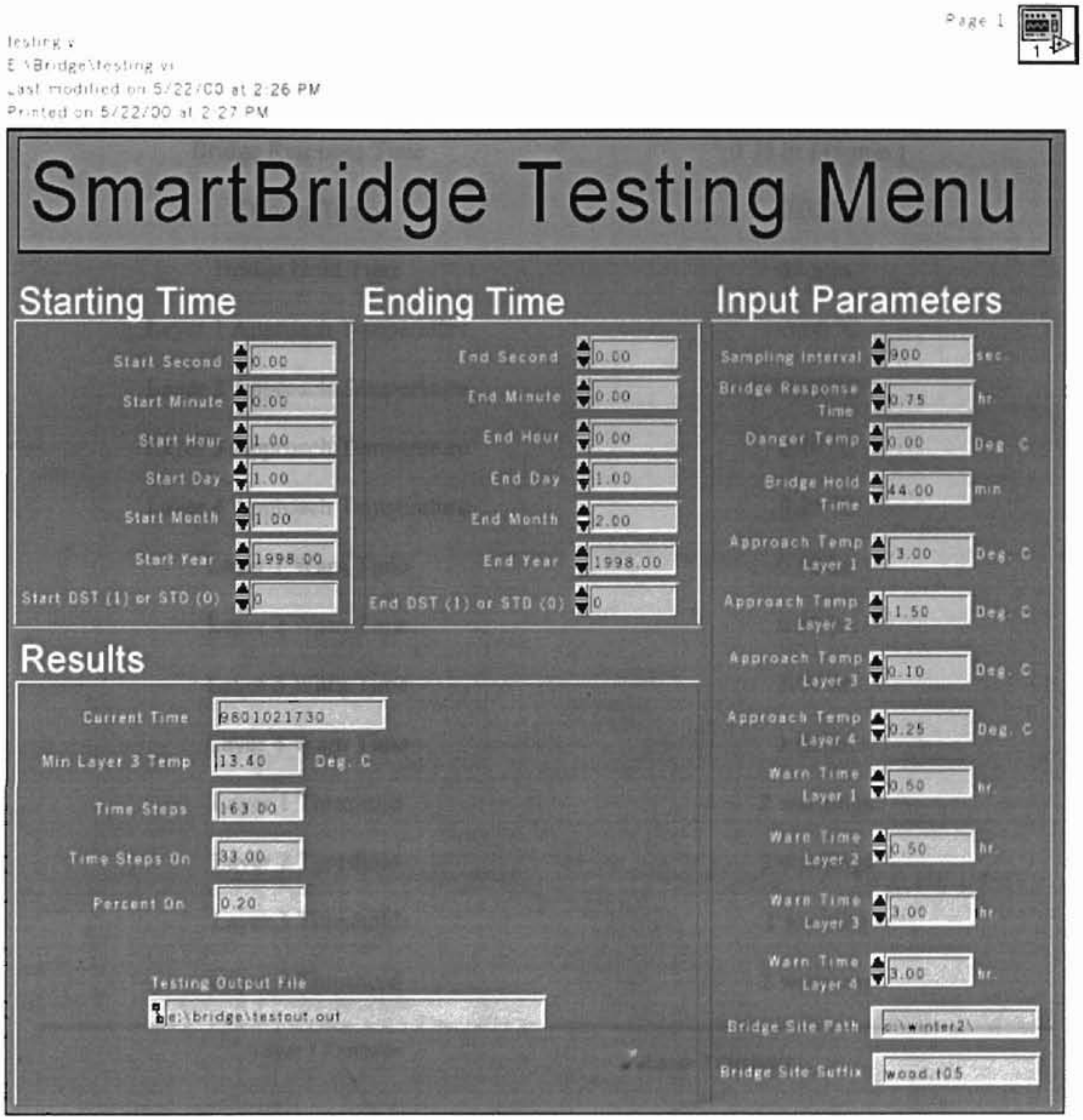
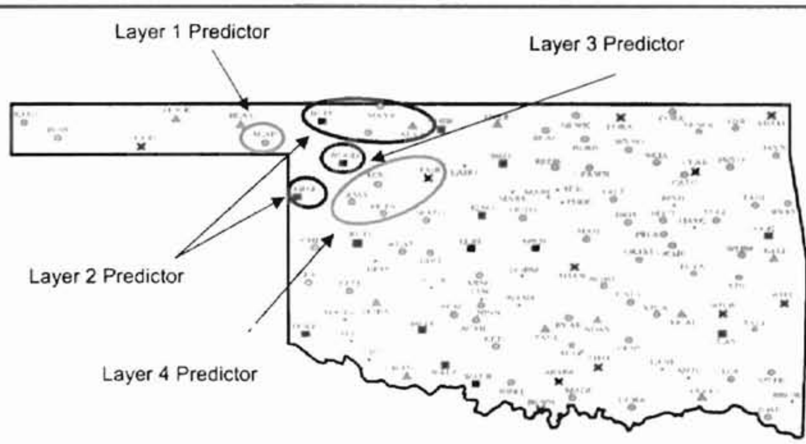


Figure 4.1 - LabView Weather Predictor Menu Screenshot

Table 4.1 - User Adjustable Parameter Values

Adjustable Parameter	Parameter Value
Sampling Interval	900 sec.
Bridge Response Time	0.75 hr (45 min.)
Danger Temp	0.00 °C
Bridge Hold Time	44 min.
Layer 1 Approach Temperature	-3.00 °C
Layer 2 Approach Temperature	-1.50 °C
Layer 3 Approach Temperature	0.10 °C
Layer 4 Approach Temperature	0.25 °C
Layer 1 Warn Time	0.50 hr.
Layer 2 Warn Time	0.50 hr.
Layer 3 Warn Time	3.00 hr.
Layer 4 Warn Time	3.00 hr.
Layer 1 Threshold	2 warnings
Layer 2 Threshold	3 warnings
Layer 3 Threshold	1 warning
Layer 4 Threshold	2 warnings



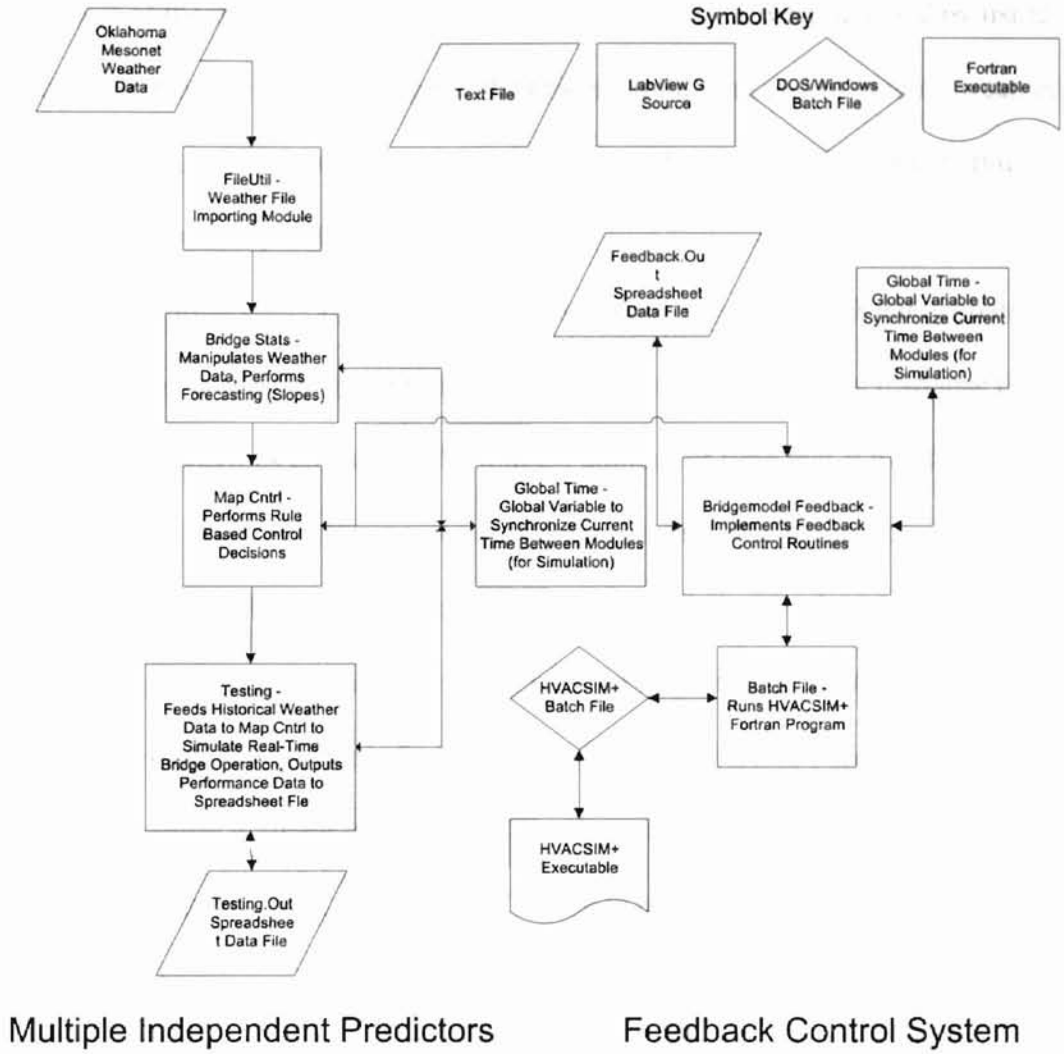


Figure 4.2 – Program Flow Diagram

Most of the user parameter values shown in Table 4.1 were selected by using good judgement based on knowledge of the bridge simulation and of general weather trends in the area. Each new installation of this control software will require similar judgement calls when specifying the parameters.

The sampling interval corresponds to the frequency of weather data updates, which was every 15 minutes (or 900 seconds) in this case. The bridge response time, as discussed in the previous chapter, is the longest amount of time that it would reasonably take the bridge to preheat in the worst weather conditions. The longest time that was returned from the HVACSIM+ bridge simulation was nearly 30 minutes. Therefore, a value of 45 minutes, corresponding to three weather station updates, was selected to be safe. The approach temperatures for Layer 1 and 2 were selected based on observing the average temperature gradient between the Woodward bridge site and the areas covered by Layers 1 and 2. On average, it is nearly 3 °C cooler in Slapout, Oklahoma (Layer 1) than in Woodward. Similarly, temperatures in Layer 2 cities are generally 1.5 °C cooler than Woodward. Therefore, approach temperature values of -3 °C and -1.5 °C were used for Layers 1 and 2, respectively. Values of 0.10 °C and 0.25 °C for Layers 3 and 4, respectively, were chosen to ensure conservative bridge deck control.

Warn time values of 0.5 hours was set for Layers 1 and 2, meaning that a controller warning would be issued if the temperature gradient (forecasted value) showed that the ambient temperature would drop below the approach temperature of the layer in 30 minutes or less. Likewise, 3 hour warn times were set for Layers 3 and 4 to ensure conservative, proactive bridge deck temperature control. Finally, the layer threshold values were set so as to ensure that cold weather fronts would not be missed, while minimizing "false alarms" caused by malfunctioning weather equipment. Since Layer 1 is represented by only one weather station (Slapout), two warnings (i.e. low temperature and low 30 minute forecasted temperature) would be required before the Layer 1 controller would signal to begin the bridge preheating sequence. In Layer 2, a combination of 3 warnings from any of the 5 weather stations in the layer would need to be active before the controller would begin bridge preheating.

Results

Figures 4.3 through 4.10 illustrate the result of the simulation utilizing the weather predictors. Figure 4.3 compares the performance of the simulated bridge using the control decisions based on the weather predictor model with the performances of both a manual operator and an idealized optimal control algorithm.

The manual operator estimation assumes that the Department of Transportation has access to perfect weather forecast information, and is therefore able to send an operator to the bridge site to turn on the heating system whenever cold weather is forecasted. It is further assumed that the department will only either turn on or turn off the bridge heating system once per day. It was assumed that the operator would either turn on or turn off the bridge once per day at exactly midnight, in response to the upcoming day's weather forecast. That is, if the ambient temperature at the bridge deck were forecasted to be equal to or lower than 0 °C at any time during the upcoming day, the operator would turn the bridge on. If not, the bridge would be turned off.

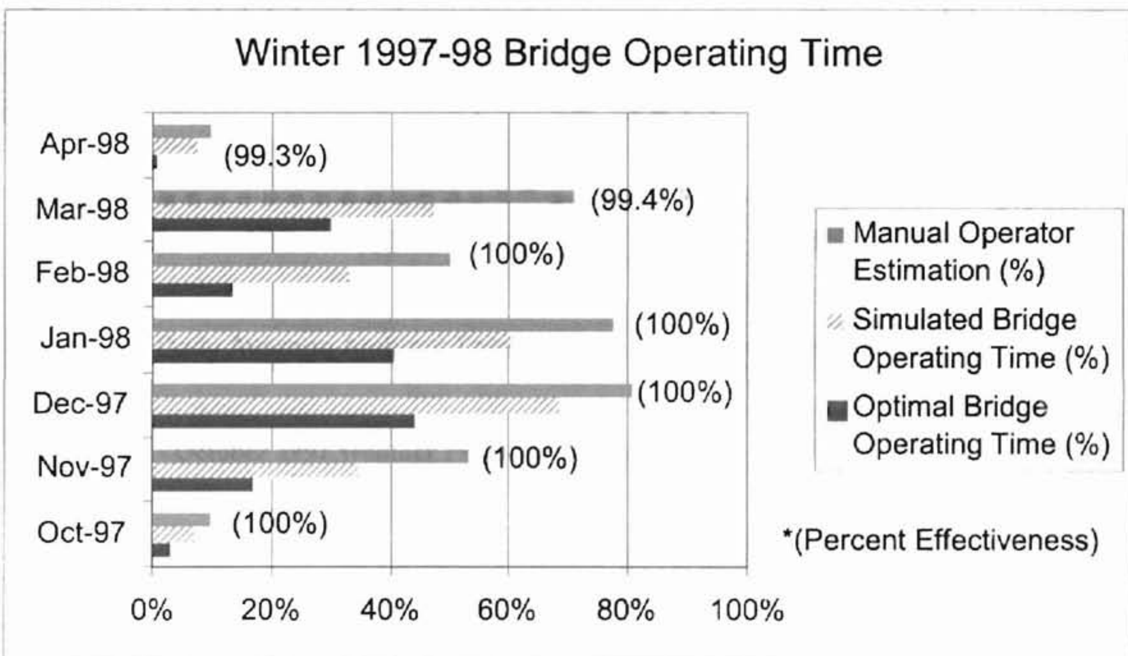


Figure 4.3 - Winter 1997-98 Bridge Operating Time

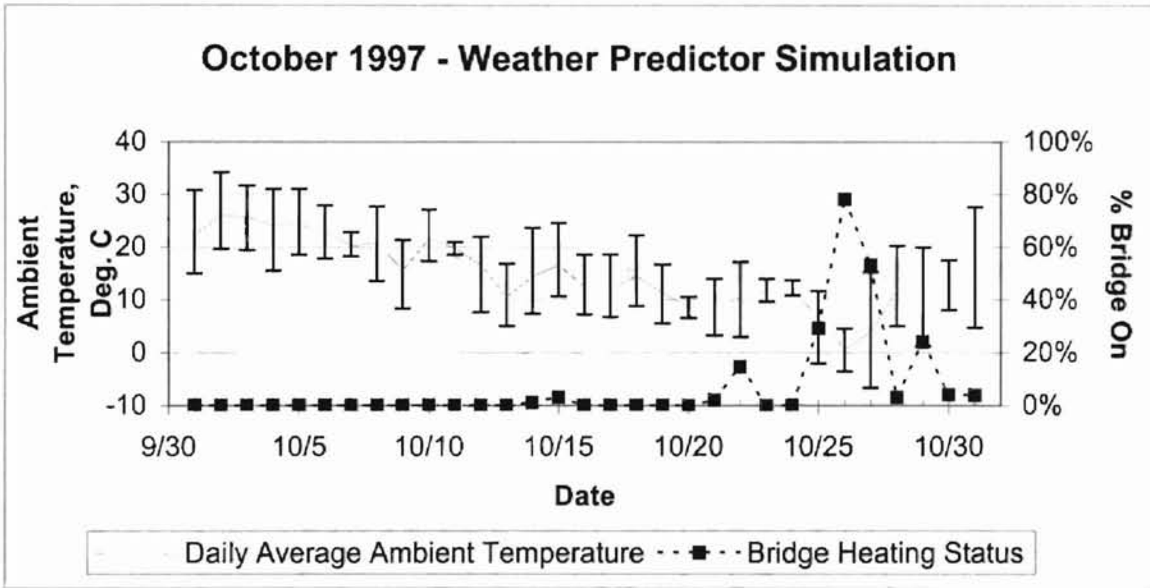


Figure 4.4 - October 1997 Weather Predictor Simulation

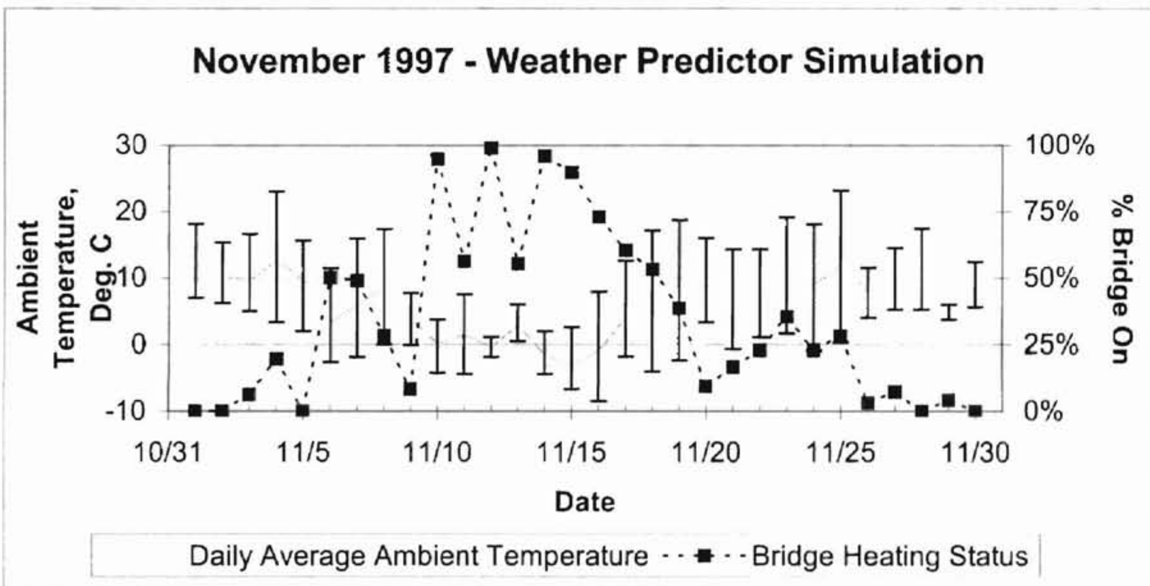


Figure 4.5 - November 1997 Weather Predictor Simulation

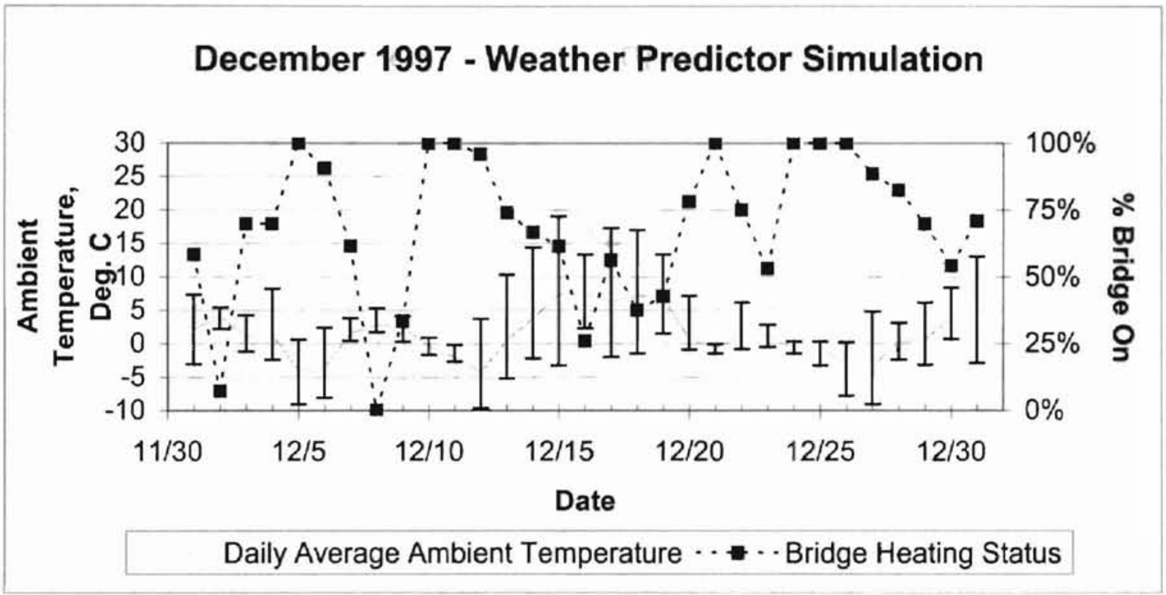


Figure 4.6 - December 1997 Weather Predictor Simulation

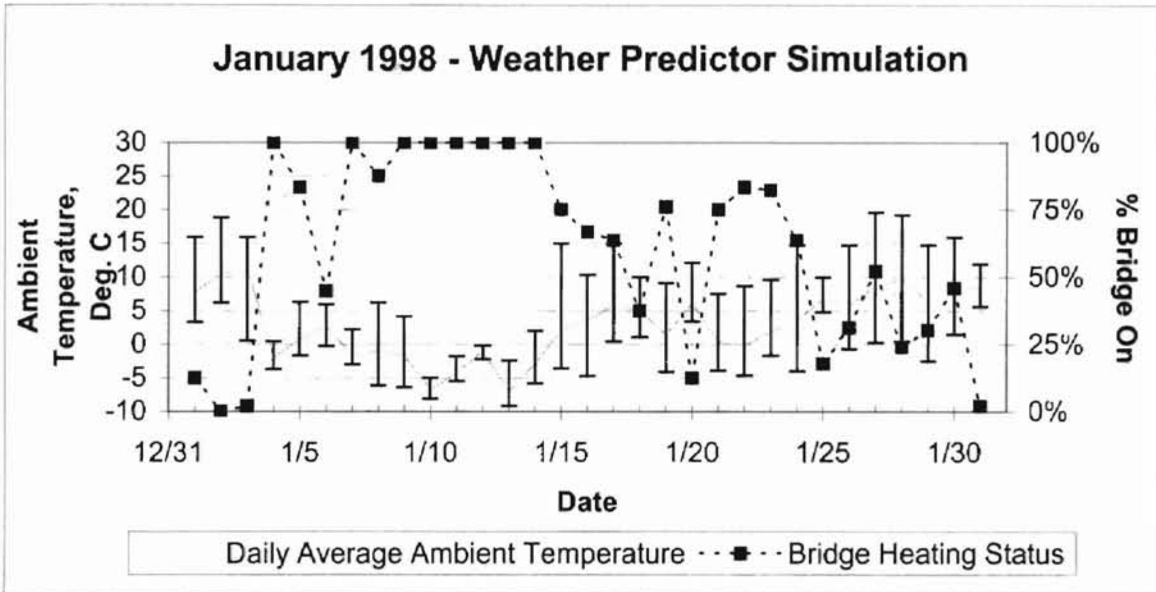


Figure 4.7 - January 1998 Weather Predictor Simulation

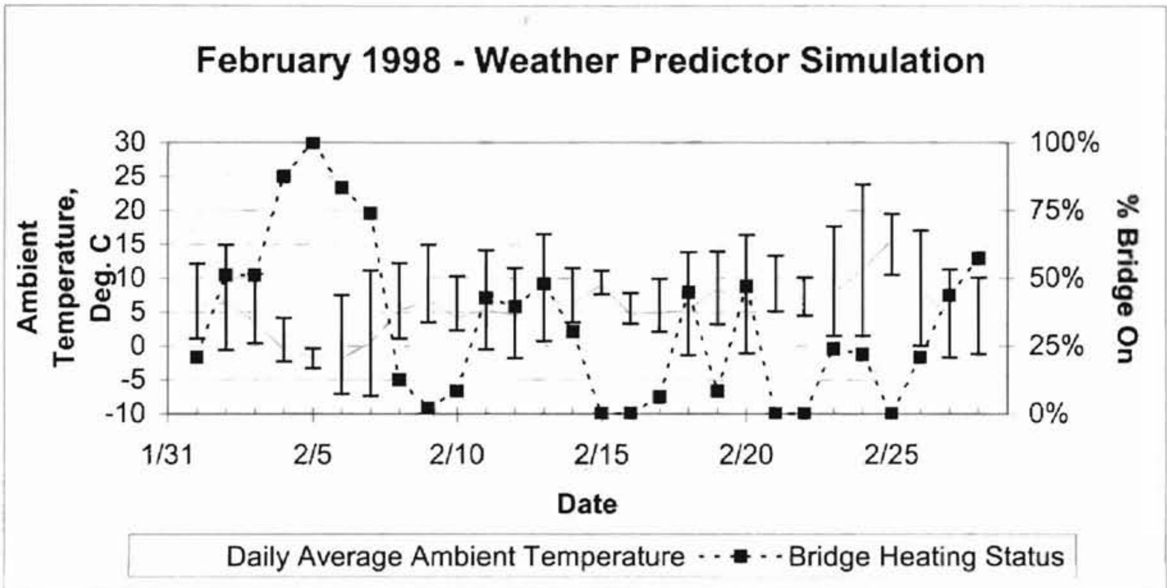


Figure 4.8 - February 1998 Weather Predictor Simulation

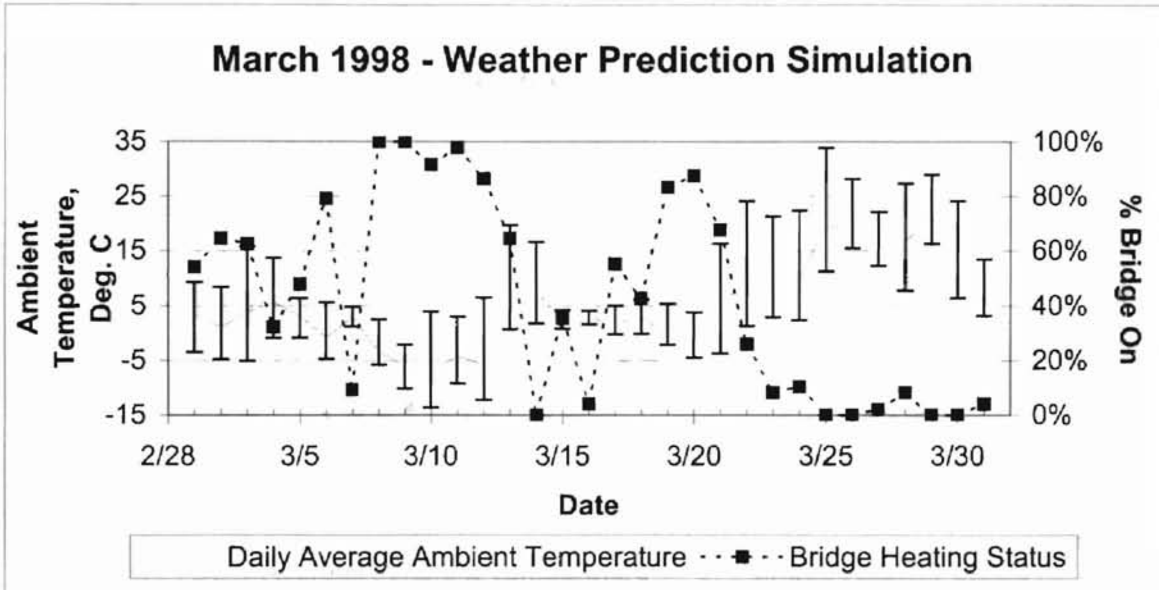


Figure 4.9 - March 1998 Weather Prediction Simulation

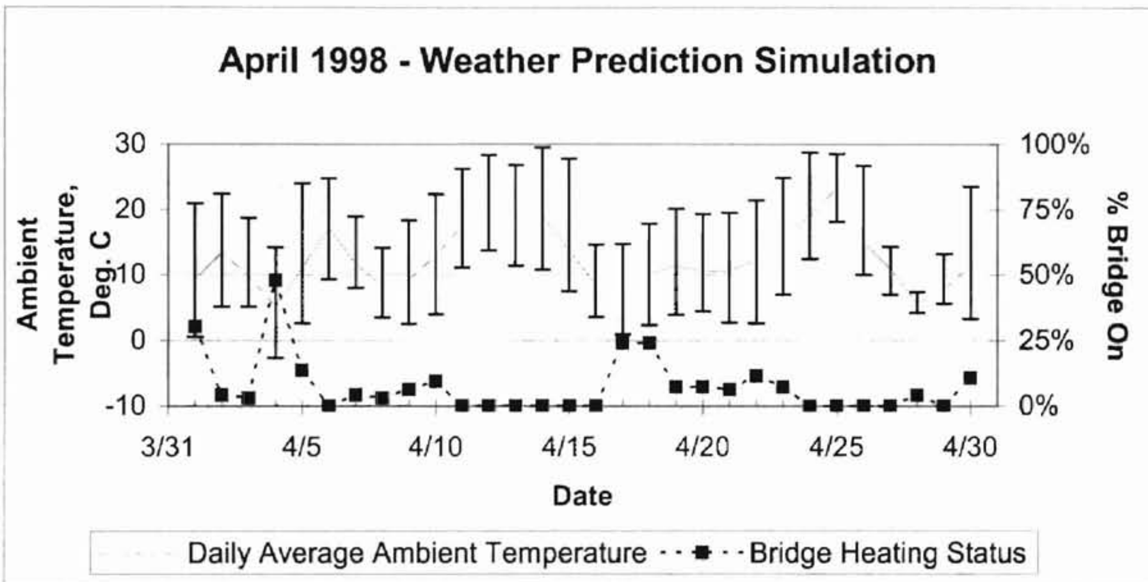


Figure 4.10 - April 1998 Weather Prediction Simulation

The optimal bridge operating time is the length of time that the bridge would need to be operating if the weather prediction algorithm were perfect. In this case, it is assumed that the bridge deck heating system operated only when the ambient temperature was below freezing. The simulated bridge operating time based on the rule-based MIP weather prediction algorithm is the amount of time the bridge heating system was operating based on the default set of parameters being used for weather prediction.

As is illustrated by Figure 4.3, the current MIP algorithm does significantly decrease the total bridge operating time. Averaged over the seven month period, simulated results using the rule-based MIP control algorithm were 26.6% more efficient than the manual operator case. The weather prediction algorithm had the bridge heating system on for 1886 hours over the entire winter, correlating to 37% of the total winter. In comparison, the manual operator estimation would have had the bridge turned on for a total of 2568 hours, or 50.5% of the winter. The optimal bridge operating time was 1093 hours, or 21% of the winter.

Despite the efficiency improvement with the simulated rule-based MIP control scenario, the effectiveness (safety factor) of the heating system was still excellent, averaging 99.8%. This means that the bridge deck heating system was operating 99.8% of the time that it was required due to cold weather.

Figures 4.4 through 4.10 show the performance of the control system by month. The black dots accompanied by the dotted line represent the bridge operating status, while the solid black line tracks the average ambient temperature. The error bars represent the daily maximum and minimum ambient temperatures, for perspective.

Conclusions

The decrease in bridge operating time does further the primary project goal of reducing the anti- and de-icing costs associated with the ground source heat pump bridge deck heating method. This reduction in bridge operating time impacts our goal in the following ways:

- Bridge Runs Less = Lower Operating Costs
- Lower Heating Load = Lower Capital Costs
- Motorist Safety NOT compromised

First, as the total bridge operating time is reduced, so are the operating costs associated with powering the heat pump compressor. Secondly, reducing the required heating load decreases the capital costs of the ground loop, primarily by reducing the number of ground loop bore holes needed to heat the ground loop fluid used in conjunction with the heat pump to warm the bridge deck. Finally, it was proven that the strides made in decreasing total bridge operating time when compared to the performance of a manual operator did not adversely effect the safety of motorists.

CHAPTER V

FEEDBACK CONTROL OVERVIEW

The second important piece of the Smart Bridge control system is the feedback, or regulatory component. The feedback controller is used to make continuous adjustments to ensure that the temperature of the bridge deck remains at the setpoint whenever cold weather is either approaching or already in the area of the bridge site. The feedback controller is activated whenever the weather prediction algorithm determines that the bridge needs to be heated. General information describing the techniques used to design the feedback controller is included in the following sections of this chapter. The evaluation of the controller algorithms described below with data simulated by the HVACSIM+ modeling software is included in the next chapter.

Methodology

Several control algorithms were examined to determine each methods suitability for the SmartBridge. The methods attempted were:

- PID using ITAE design rules
- Smith Predictor
- Dahlin's Controller

PID Using ITAE Design Rules

Feedback process control using the proportional, integral, and derivative (PID) control algorithm has been used in the process industries since the 1930s [90]. PID feedback control uses the error, or difference, between the desired value and the current value of a controlled variable to calculate the changes to the manipulated variable needed to drive the error to zero. Error between the desired and actual values of the controlled variable commonly occur due to unmeasured disturbances.

The controlled variable for this bridge deck control problem is the average bridge deck temperature. While the average bridge deck temperature would be difficult to measure in reality, the variable is available as an output from the HVACSIM+ program used to model the performance of the bridge deck. The manipulated variable is the ground loop flow rate. By increasing the ground loop flow rate, more heat is delivered to the heat pump, which is then transferred to the bridge deck fluid.

The general equation for the PID control algorithm is shown in Equation (1). The proportional term calculates a new value for the manipulated variable (ground loop flow rate) proportional to the currently measured error. The integral term is proportional to the integral, or total, error. Finally, the derivative term is proportional to the derivative, or rate of change, of the error signal. The digital version of the PID control law is shown in Figure 5.1.

$$m(t) - \overline{m} = K_c e(t) + \frac{K_c}{\tau_I} \int e(t)dt + K_c \tau_d \frac{de(t)}{dt} \qquad (1)$$

Proportional term — Integral term — Derivative term

PI Controller

The standard digital PI controller was used as follows:

$$gc(z,\theta) := \frac{\theta_0 + \theta_1 \cdot z^{-1}}{1 - z^{-1}}$$

$$\theta_0 = K_c \cdot \left(1 + \frac{\Delta t}{\tau_I}\right)$$

Standard ITAE (disturbance) design rules were used to determine the tuning parameters.

$$\theta_1 = -K_c$$

Smith Predictor

$$gc(z,\theta,\psi,D) := \frac{\theta_0 + \theta_1 \cdot z^{-1}}{1 + \psi_1 \cdot z^{-1} + \psi_D \cdot z^{-D}}$$

$$\theta_0 = \frac{\tau + \Delta t}{K \cdot (\tau_r + \Delta t)}$$

$$\theta_1 = \frac{-\tau}{K \cdot (\tau_r + \Delta t)}$$

$$\psi_1 = \frac{-\tau_r}{\tau_r + \Delta t}$$

$$\psi_D = \frac{-\Delta t}{\tau_r + \Delta t}$$

τ = "Process Model Time Constant"

K = "Process Model Gain"

τ_r := "Reference Trajectory Time Constant"

$$D := \frac{\text{"Process Delay"}}{\Delta t}$$

Dahlin Controller

$$gc(z) = \frac{\tau \cdot (1 - z^{-1}) + 1}{K} \cdot \frac{(1 - \phi_r) \cdot z^{-M-1}}{1 - \phi_r \cdot z^{-1} - (1 - \phi_r) \cdot z^{-M-1}}$$

$$gc(z) = \frac{\frac{1}{K} \cdot \left[(1 - \phi_r) \cdot (\tau + 1) \cdot z^{-2} - (1 - \phi_r) \cdot \tau \cdot z^{-3}\right]}{1 - \phi_r \cdot z^{-1} - (1 - \phi_r) \cdot z^{-2}}$$

where M=1

τ = "Process Model Time Constant"

K = "Process Model Gain"

$$\phi_r = e^{\frac{-\Delta t}{\tau_r}}$$

$$M := \frac{\text{"Process Delay"}}{\Delta t}$$

Figure 5.1 – Digital Control Laws

The $\overline{m}$ term in equation (1) is the steady state value of the manipulated variable. The parameters K_c, τ_I, and τ_D are the user-adjustable values for the proportional gain, integral time, and dead time, respectively. The error signal is denoted by $e(t)$.

The values selected for the user-adjustable parameters determine the performance of the PID feedback control algorithm. Many guidelines exist to aid in the selection of these parameters. One of the more popular guidelines, and the one used here, is the ITAE (Integral of Time-Weighted-Absolute Error) tuning rule.

The ITAE tuning rule is based on empirical observations, not on theory. The ITAE typically produce conservative values for the tunable parameters [90]. The ITAE definition is shown in Equation (2).

The block diagram for the standard PID feedback controller is shown in Figure 5.2.

$$ITAE = \int_0^\infty t|e(t)|dt \qquad (2)$$

Model Based Control

While the PID control algorithm determines manipulated variable changes based solely on an error signal, a family of algorithms described as model predictive control techniques utilize mathematical models of a process to aid in the control of a process. The Smith Predictor and the Dahlin Controller are both examples of model predictive controllers. These two methods are described below.

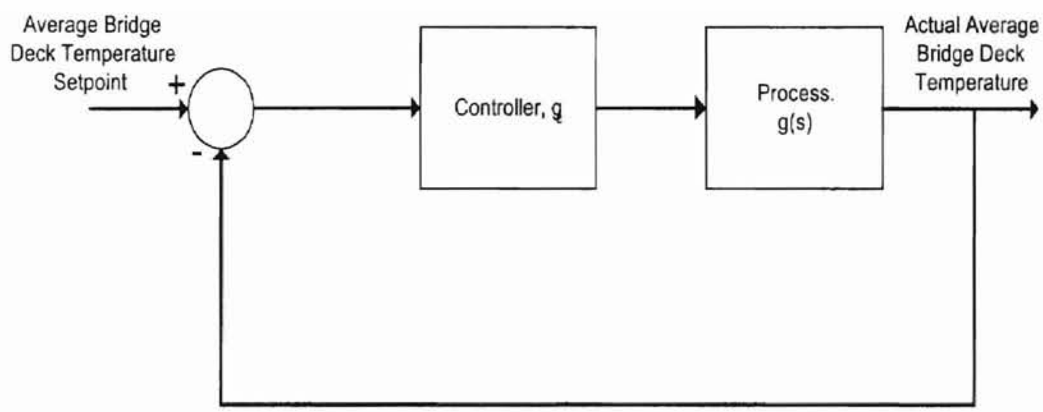


Figure 5.2 – Simplified Feedback Control Diagram

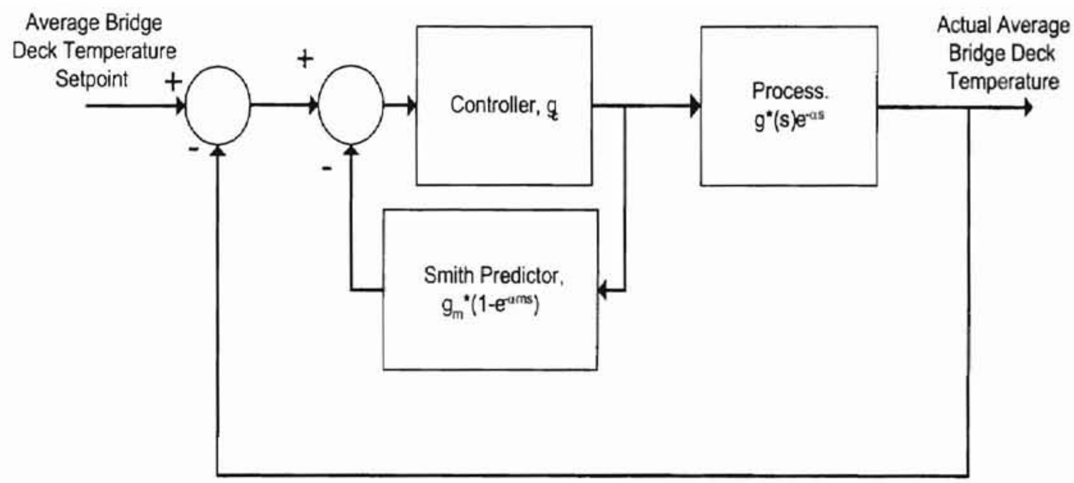
Smith Predictor

Classical techniques, such as PID control, don't specifically handle time delay. Instead, the PID control parameters must be detuned to address time delay. The Smith Predictor is a technique that is designed to primarily compensate for time delays associated with a process. In the Smart Bridge project, the time it takes for pumps to respond after being switched on, and the time lag associated with pumping the hot ground loop water to the heat pump are both examples of time delay. While these delays are not yet modeled in the HVACSIM+ simulation software, they will be real phenomenon when the actual bridge deck heating system is put into operation. Currently, however, there is a 60 second delay between the time that a ground loop flow rate setpoint change is made in the control software and the time that the simulation actually begins to change the flow. This one minute delay is accounted for by the Smith Predictor control algorithm,

Figure 5.3 illustrates the block diagram of a controller incorporating a Smith Predictor. The digital version of the Smith Predictor controller equation was presented previously in Figure 5.1.

Dahlin Controller

The Dahlin Controller is an example of a model based algorithm designed via the direct synthesis method. The direct synthesis method is used to attempt to force the controlled variable to follow a user-specified reference trajectory. The control moves needed to achieve the desired trajectory are calculated using a model of the controlled process.



$e^{-\alpha s}$ - Process Delay Term
$e^{-\alpha ms}$ - Process Model Delay Term
$g_m(s)$ - Process Model
$g_c(s)$ - Controller Transfer Function
$g^*(s)$ - Undelayed Process Transfer Function

Figure 5.3 – Smith Predictor Block Diagram

The Dahlin controller attempts to impose a trajectory similar to that shown in Figure 5.4. The Dahlin controller trajectory is idealized and requires that the controlled variable progress towards the setpoint along a defined first order plus time delay path.

The mathematical representation for the Dahlin Controller in the discrete time (z) domain was shown in Figure 5.1. The Dahlin Controller has two adjustable parameters, M and τ_r. M is a representation of the number of sample periods associated with the model delay. τ_r, or the reference time constant, is an adjustable parameter representing the controller aggressiveness. The smaller the value of the reference time constant, the more aggressive the controller becomes.

Conclusion

In this chapter, several possible feedback control algorithms capable of regulating the Smart Bridge were reviewed. Each of the techniques requires a set of user adjustable parameters to describe the algorithm characteristics. Obviously, the specification of the adjustable parameters associated with each algorithm will strongly influence performance. Details concerning parameter specification for the Smart Bridge controller are located in the following chapters.

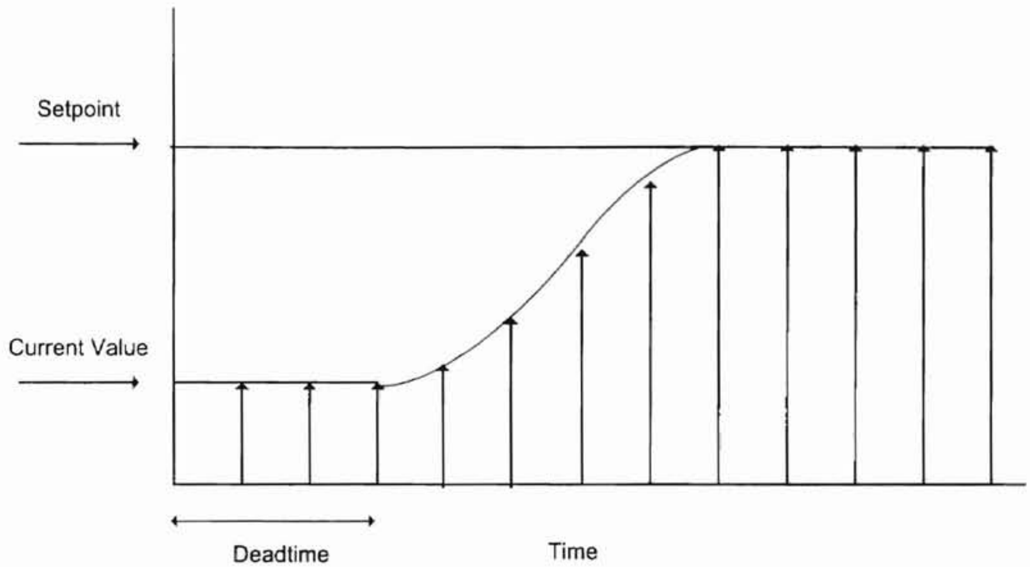


Figure 5.4 – Dahlin Controller Trajectory

CHAPTER VI

FEEDBACK CONTROL CASE STUDIES

Since this work is the first stage in a multi-year development of a geo-thermally heated bridge deck control system, some unique challenges needed to be overcome in order to provide an evaluation of the performance of potential feedback control algorithms. The most important of these challenges is the fact that there is no physical system with which to test. Instead, only a finite-difference model, programmed using a Fortran-based model called HVACSIM+, is available. In addition, the HVACSIM+ model is also in its initial development phase, so the model only provides a rough estimate of the actual bridge response. These difficulties are discussed in the following section, followed by a section outlining the results from the feedback performance tests done using a conventional PI controller, a Dahlin controller, and a Smith Predictor controller.

HVACSIM+ Finite Difference Model

HVACSIM+ is an open-source collaboration between the National Institute of Standards and Technology and interested parties in academia and industry. HVACSIM+ is being used for the Smart Bridge project to break each of the three main elements of the system (the bridge deck, the heat pump(s), and the ground loop) into separate components. The program predicts dynamic temperature profiles of the components in response to different weather inputs as well as operating conditions.

The main advantage for using the HVACSIM+ code for the Smart Bridge project is the free license, which means that the simulation embedded in the controller can be distributed at no cost. However, a user friendly interface is not provided in HVACSIM+, so integration of the simulation software with the control system is difficult. A companion technical report to this thesis is available, which describes how the interface between the LabView-based control system and HVACSIM+ was constructed [9].

There are three main challenges with the current version of the Smart Bridge simulation using HVACSIM+ that impact the feedback control study. These three problems are that the simulation utilizes only one heat pump, that the simulation is unable to switch between "bridge on" and "bridge off" conditions without locking up, and finally that large changes in the ground loop flow rate (> 0.75 kg/s) result in a short period of unreliable results. The following sections discuss these problems.

Single Heat Pump

As pointed out in Chapter IV, the current HVACSIM+ simulation uses a single heat pump sized to run under a narrow range of operating and weather conditions. In order to be able to maintain an average bridge deck setpoint of 0.83 °C, the ambient weather conditions must be fairly severe, as shown in Table 6.1. Less severe conditions, with the ambient temperature closer to 0 °C, and the wind decreased to five meters per second from 15 meters per second, would cause the minimum attainable average bridge deck temperature to increase to about 9 °C. While the bridge is certainly still protected from icing at this higher temperature, more heat than necessary is being taken from the ground loop and wasted. The heat pump is unable to scale down the heat load because of

Table 6.1 – Simulated Weather Conditions

Simulated Weather Conditions

	Standard Model	Perturbed Model
Ambient Temperature (Deg. C)	-5	-6
Sky Temperature (Deg. C)	-11	-13
Wind Speed (m/s)	14	11
Rainfall (mm/hr)	10	10
Solar Radiation (W/m^2)	0	0
Relative Humidity	100%	100%

minimum limits on both the heat pump compressor and the ground loop flow rate. In order to compensate for the scaling problems in this first stage of bridge development, the assumption made when developing the feedback controllers was that the ambient conditions were always similar to those listed in Table 6.1. These conditions are severe enough that 0.83 °C is attainable.

In the next version of the HVACSIM+ model, multiple heat pumps will be available. Heat pumps will be able to be turned on and off, and be configured in parallel and series flow arrangements to compensate for differing heating requirements. Figure 6.1 shows a proposed configuration. The system shown in the figure represents 1/8th of the actual bridge heating system. So, while the figure shows two heat pumps plumbed in series, the planned full sized bridge will have 16 total heat pumps available, or 8 pairs in series.

The feedback control strategy for the multiple heat pump case shown in Figure 6.1 is different from the one described in the previous chapter. Essentially, the multiple heat pump case will add one additional manipulated variable to the control system. The feedback control system described in the last chapter had the ground loop flow rate as the sole manipulated variable, and the average bridge deck temperature as the sole controlled variable. In the multiple heat pump case, the ground loop flow rate and a new variable termed "percent of capacity" are the manipulated variables, with the average bridge deck temperature remaining the sole controlled variable. The "percent of capacity" variable would control how many heat pumps are actually turned on at any one time. Additionally, rules would be created to determine the most energy efficient flow arrangement corresponding to each percent of capacity value. For instance, if 50%

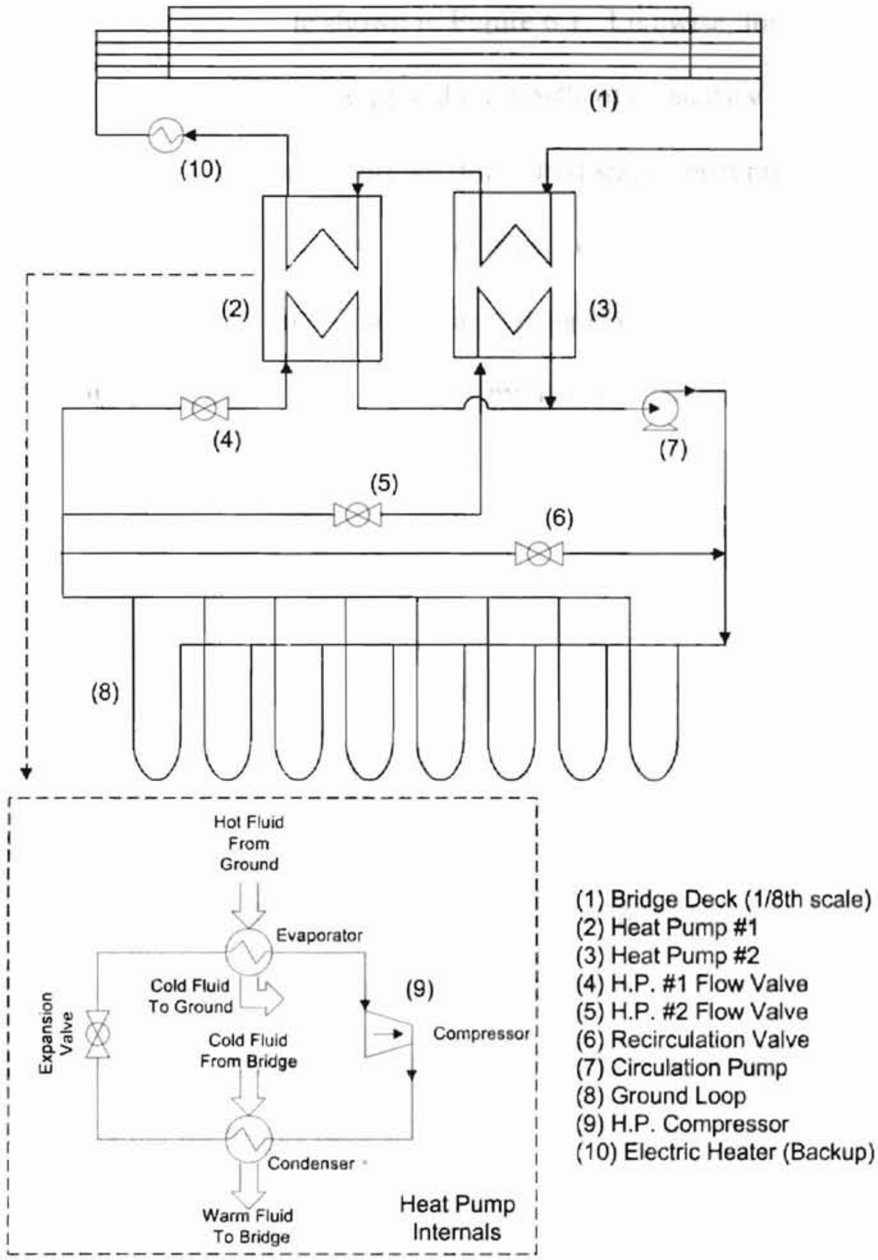


Figure 6.1 - Future Multiple Heat Pump Configuration

capacity were desired, the control system would turn on heat pump #1 and shut off heat pump #2 in the 1/8th scale example shown in Figure 6.1. Likewise, four heat pumps on the actual full scale bridge would be turned on if 50% of capacity was desired. If 75% of capacity was desired for a full scale bridge, four "first stage" heat pumps would be switched on, and two "second stage" heat pumps in series (corresponding to heat pump #2 in Figure 6.1) would be turned on. This additional sophistication would solve the problem associated with using a large, single heat pump that is often oversized and inefficient for many weather conditions.

Switching from "Bridge On" to "Bridge Off"

One of the features that is important for the bridge simulation to have is the ability to track the bridge temperature profile even when the heating element is turned off. This is important because the temperature of the bridge deck surface can not be assumed to be equal to the ambient air temperature. The bridge deck surface temperature is, in fact, a function of many additional variables, including the sky temperature, solar radiation, precipitation rates, and the effects from the previous heating cycle. Therefore, the bridge simulation should be simulating the bridge deck response even when the heat pump is turned off. Not running the simulation during times when the heat pump is not turned on would cause the heat load during the next heating cycle to be either underestimated or overestimated due to inaccurate initial simulated conditions. Currently, however, the HVACSIM+ bridge model is unable to switch to a "bridge on" condition from a "bridge off" condition without frequently locking up. Therefore, until this problem is solved, the bridge deck temperature is always assumed to be equal to the ambient air temperature during startups.

Large Control Moves

As discussed in the previous chapter, the feedback controller is single-input, single-output (SISO). The controlled variable is the average bridge deck temperature returned by the simulation. The manipulated variable is the ground loop flow rate. Unfortunately, the current simulation is unable to converge during the first minute or two after a large (>0.75 kg/s) change is made to the ground loop flow rate. In fact, the results returned by the simulation after making such a large move show inverse response. That is, when the ground loop flow rate is increased, the average bridge deck temperature is shown to decrease. This is not a reasonable physical phenomenon, and is believed to be due to a convergence error internal to HVACSIM+. Therefore, the controller has to be configured in such a way as to minimize the possibility of making such a large control action. This procedure is called detuning, and results in the control system to be more sluggish. This sluggishness increases the time it takes to level out at a desired setpoint value.

Testing Methodology

Each control algorithm was tested by using the National Instruments Labview control software. The LabView package was used to implement the digital control algorithms, while calling the HVACSIM+ Fortran-based finite difference heat transfer package to simulate the dynamic response of the bridge. The modeled process consists of a single heat pump which transfers heat from a ground loop at approximately 14 °C to the bridge, which is operated under user-defined weather conditions (Table 6.1).

The control algorithms are compared using two different cases for ambient weather conditions. The "Standard Model" case and the "Perturbed Model" case shown in Table 6.1 are somewhat similar because of the constraints imposed by using only one heat pump to service the bridge, as discussed previously. The Perturbed Model is simply being used to illustrate the effects of model mismatch on the controllers that performed well under the Standard conditions.

Each control algorithm was designed utilizing a first-order plus time delay model developed from the response of the Standard Model weather conditions (Figures 6.2 and 6.3). The mathematical expressions for the controllers are the same as those shown in Figure 5.1. Tuning of each algorithm was done using the following methods:

- Integral of the Time-Weighted Average Error (ITAE) for PID
- Response Time Constant of 5.0 minutes for the Smith Predictor (4x Process Time Constant)
- Response Time Constant of 5.0 minutes and M (Delay) of 1.0 minutes for the Dahlin Controller

Results

Figure 6.4 through 6.12 show the results of the controller performance tests. Table 6.2 summarizes the performance of the algorithms by listing the Integral Squared Error (ISE) for each test.

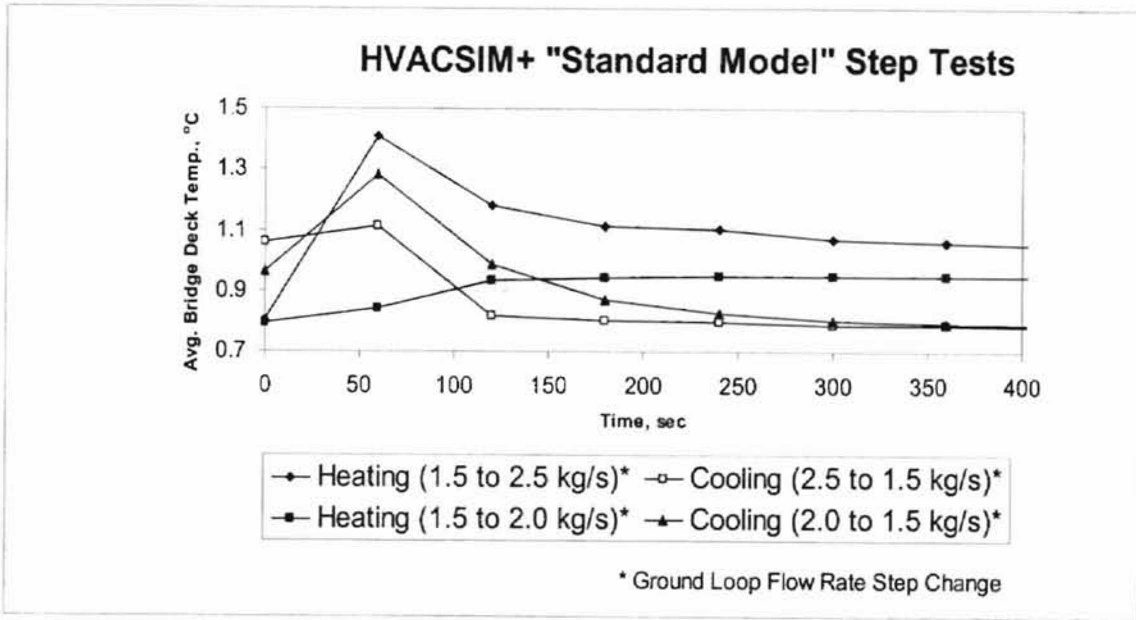


Figure 6.2 – Standard Model Step Tests

First Order Plus Time Delay Model (for Model Based Control Design)

$$g(s) = \frac{Ke^{-\alpha s}}{\tau s + 1}$$

Process Response (in Laplace Domain), g(s)

Process Gain, K

Time Delay, α

Time Constant, τ

Derived Model (from Step Tests)

$$g(s) = \frac{0.294 e^{-1 s}}{1.25s + 1}$$

Process Gain	0.294 $\frac{\text{"Degree C"}}{\text{"kg/s"}}$
Time Delay*	1 minute
Time Constant	1.25 minutes

*Time Delay not shown in graph - the time delay was added because of the 60 second lag between the time a setpoint change is entered into LabView and the time the HVACSIM+ bridge simulation receives the change.

Figure 6.3 – First Order Plus Time Delay Model

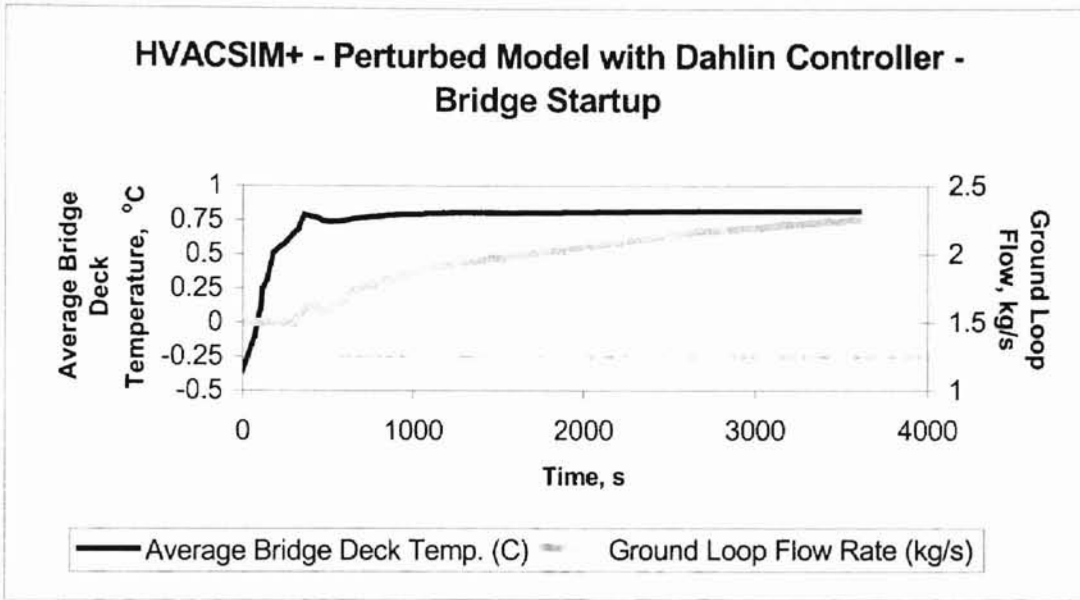


Figure 6.4 – Standard Model with PID (ITAE) Controller – Bridge Startup

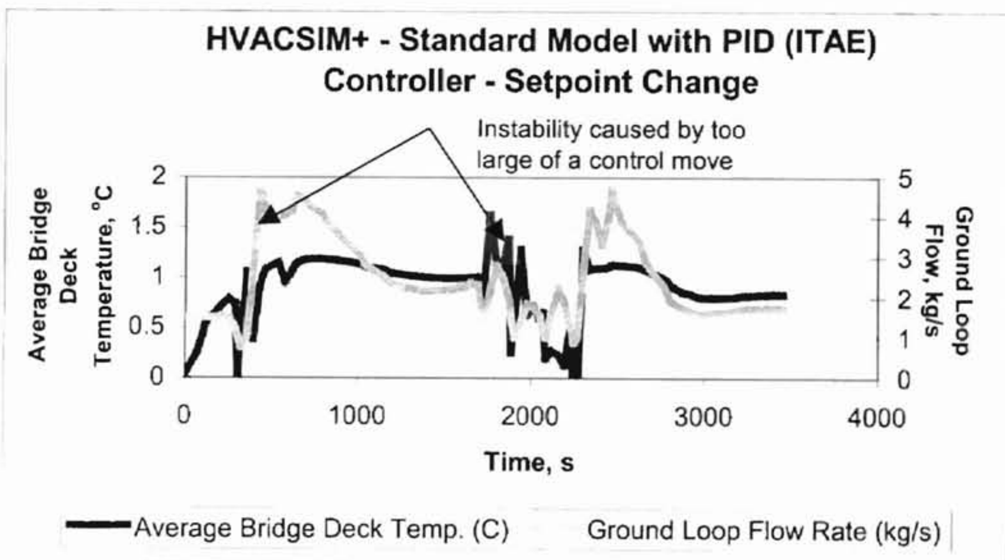


Figure 6.5 – Standard Model with PID (ITAE) Controller – Setpoint Change

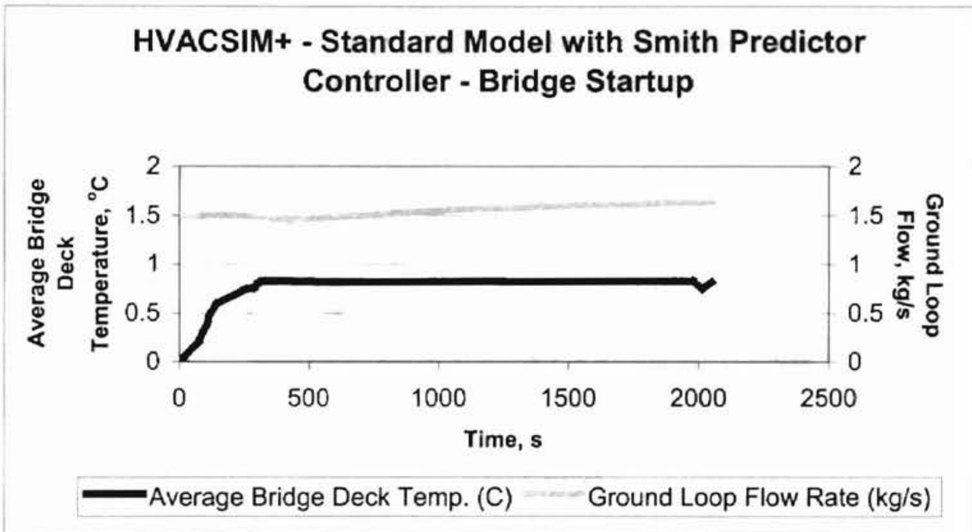


Figure 6.6 – Standard Model with Smith Predictor Controller – Bridge Startup

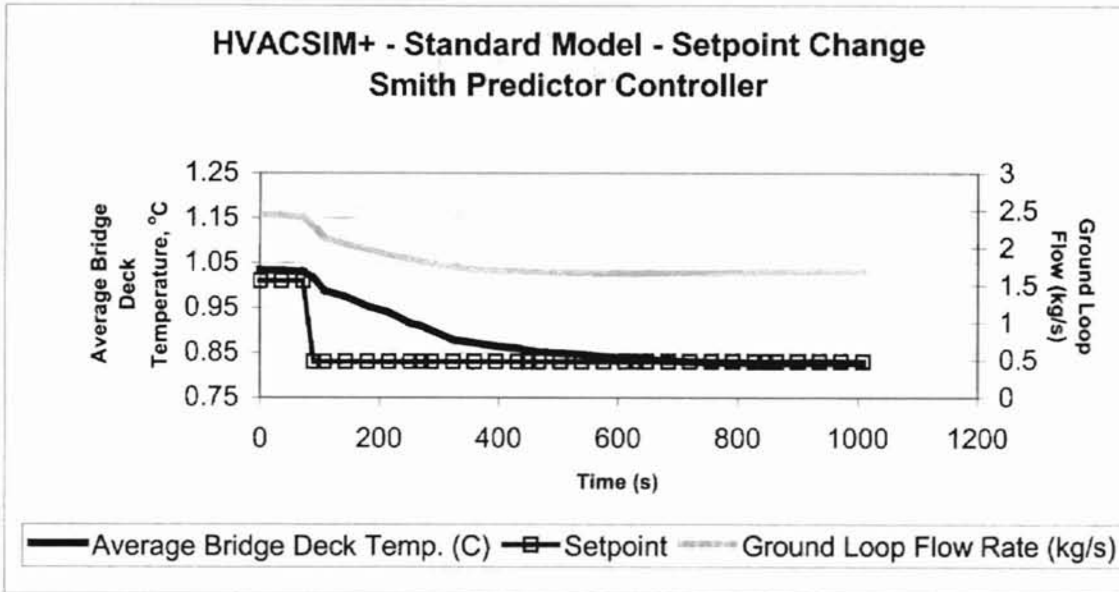


Figure 6.7 – Standard Model with Smith Predictor – Setpoint Change

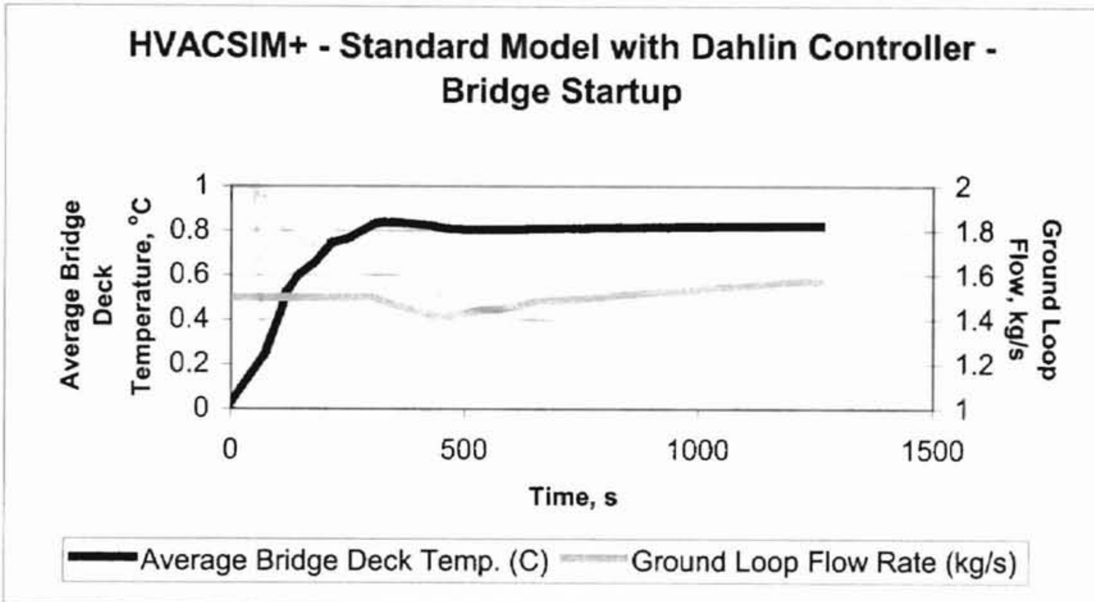


Figure 6.8 – Standard Model with Dahlin Controller – Bridge Startup

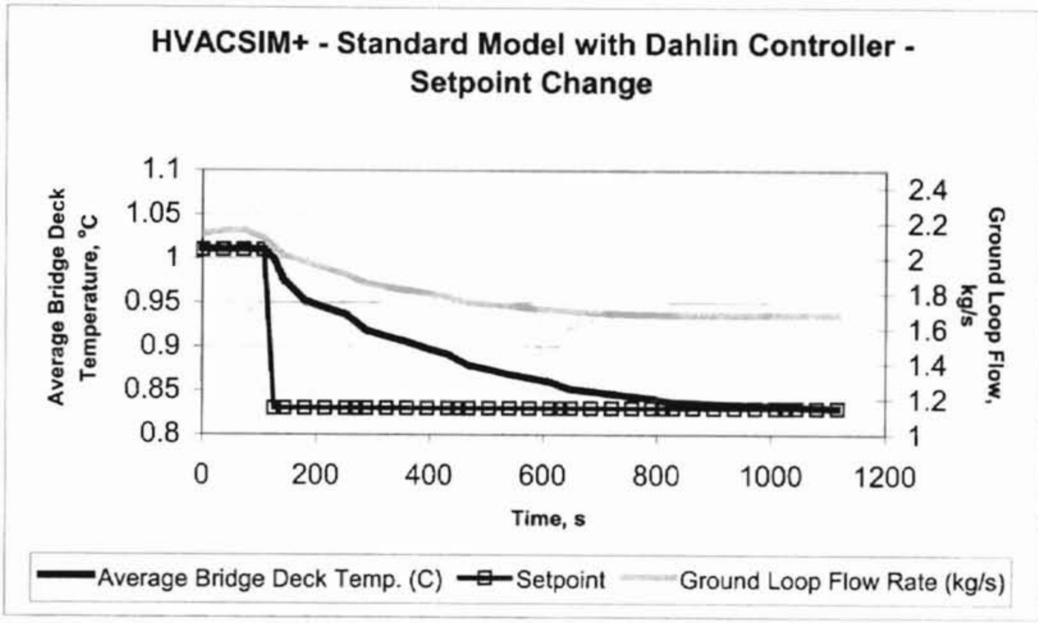


Figure 6.9 – Standard Model with Dahlin Controller – Setpoint Change

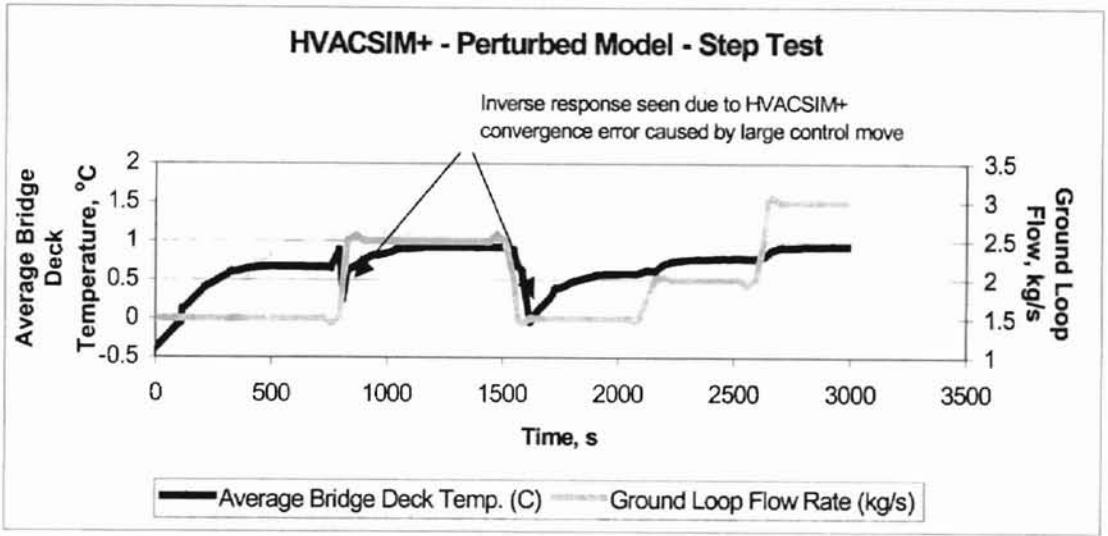


Figure 6.10 – Perturbed Model – Step Test

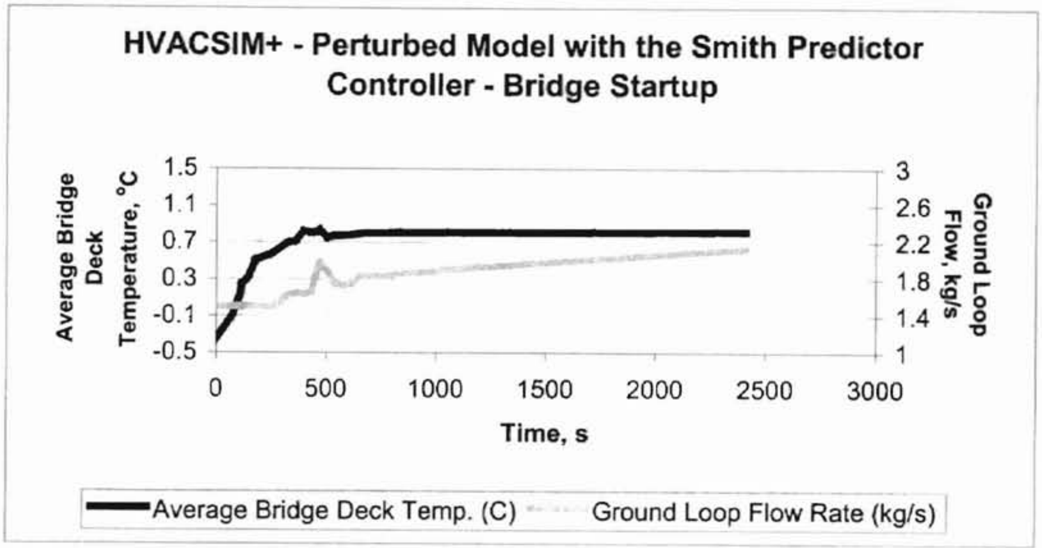


Figure 6.11 – Perturbed Model with Smith Predictor – Bridge Startup

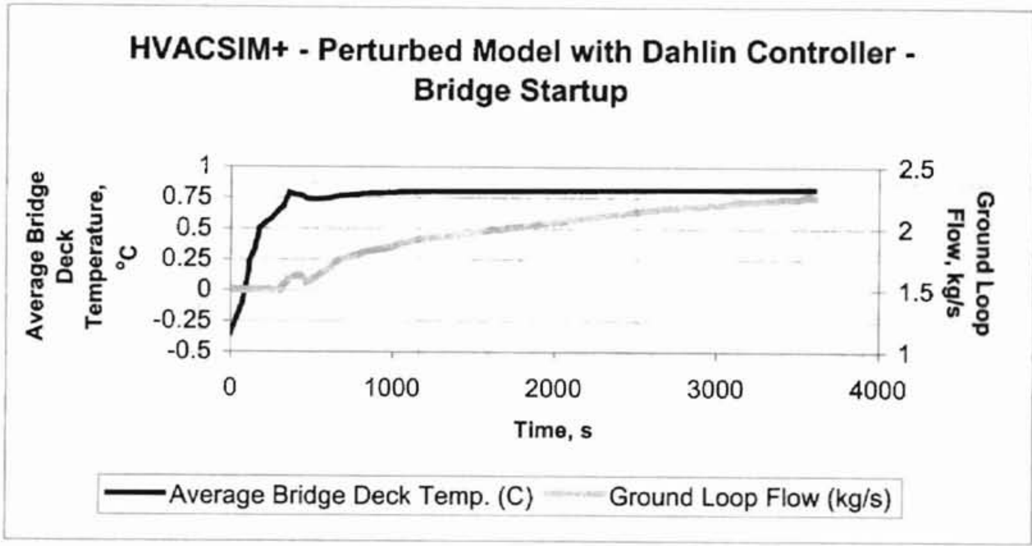


Figure 6.12 – Perturbed Model with Dahlin Controller – Bridge Startup

Table 6.2 – Controller Testing Results

Controller Testing Results

Controller	ISE - Startup*	Settling Time - Startup	ISE - SP Change*	Settling Time - SP Change
PI w/ ITAE	326.1	2000 sec.	220.7	1650 sec
Smith Predictor	74.5	360 sec.	5.75	600 sec.
Dahlin	67.2	360 sec.	4.51	1000 sec.

* Units=($^{o}C^{2}$)(sec)

Each of the algorithms were compared based on startup conditions and setpoint change conditions. The startup tests were performed by assuming that the average bridge deck temperature was 0 °C initially (-0.5 °C for the perturbed model tests). The heating system was then turned on, and the control system was setpoint was targeted at 0.83 °C. The setpoint change test was used to approximate the response of the bridge when only small adjustments to the average bridge deck temperature is required (see Figure 6.10). Small adjustments are often the required when regulatory changes are necessary, such as when the ambient temperature suddenly drops, or it starts to snow. One point to notice is that to maintain the average bridge deck setpoint, the ground loop flowrate has to be slowly increased over time. This behavior can be seen clearly in Figures 6.4 and 6.10. To explain this phenomenon, refer back to the analogy comparing the ground source heat pump to a home water heater proposed in Chapter II. Essentially, the hot water stored in the ground loop reservoir is slowly being depleted, so additional ground loop flow is needed to maintain the same heat transfer rate to the bridge deck.

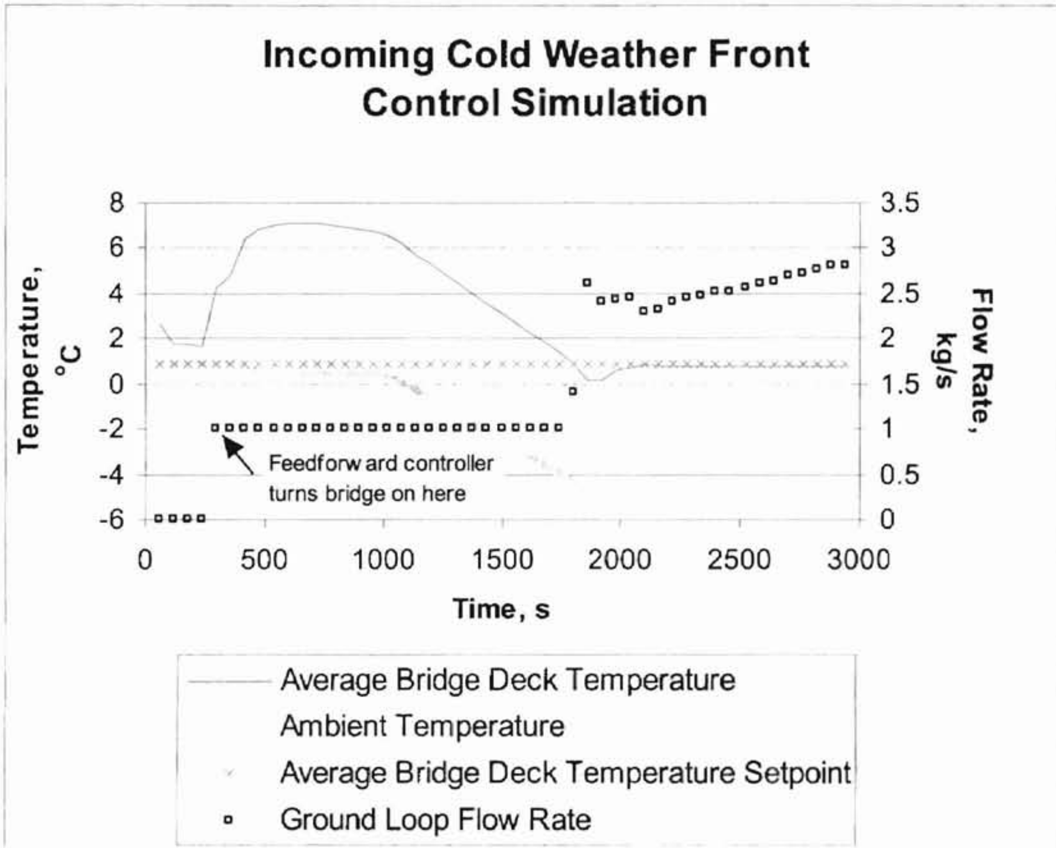
The results shown in Table 6.2 show the response time and the integral of the squared error (ISE) of the bridge in both the startup and setpoint change conditions. The response time is an estimation of the time it takes the controller to settle the average bridge deck temperature to within 99% of setpoint. The ISE is an index representing the total squared error between the actual average bridge deck temperature and the setpoint since the controller was turned on. In interpreting the results of the graph, controllers that tend to attain the desired setpoint faster are valued over similarly performing controllers that respond slightly slower. This preference is due to the importance of bridge safety, even when a bit of efficiency, represented by the ISE value, is lost.

Clearly, the model based algorithms have an advantage over the PI algorithm using standard ITAE design rules. The Smith Predictor algorithm is the best performing for this application, because it has the minimum response time in both the startup and the setpoint change categories, while the ISE values are close to the low values. The Dahlin controller also performed well, scoring the "best" as far as the Integral of the Squared Error test. However, the slower response time of the Dahlin method tends to make the Smith Predictor algorithm look the most attractive.

As an additional performance test between the Smith Predictor and the Dahlin algorithms, simulations were performed when there was intentional mismatch between the process model and the first-order plus time delay model originally used to design the controller. This mismatch was obtained by using the "Perturbed" weather conditions as inputs to the HVACSIM+ model. The process time constants used for the Smith Predictor and the Dahlin controller were both also changed from 1.25 minutes to 1.85 minutes. Figures 6.10 through 6.12 illustrate these tests.

For the "Perturbed" tests using LabView with the actual HVACSIM+ model, the Dahlin's Controller still controlled the bridge deck temperature. However, the time it took to steady out at setpoint was much larger (1000 seconds vs. 360 seconds with the Standard Model). The Smith Predictor algorithm experienced a similar phenomenon (nearly 1000 seconds vs. 360 seconds with the Standard). It is unclear whether this difference is due to the different set of weather conditions, or whether the additional time was caused by model mismatch. It is likely, however, that the additional response time was caused more by the differing weather conditions, because the controller response was still fairly smooth. Additionally, by setting a reference time constant of 5 minutes, the controller is essentially detuned enough that it doesn't make drastic changes to the manipulated variable, which could lead to instability as discussed previously.

As a final exercise, Figure 6.13 shows the results of a simulation utilizing both the weather predictor coupled with the feedback controller (using the Smith Predictor algorithm). At a time of 300 seconds, the weather predictor turns on the bridge in response to a temperature warning issued by Layer 2 of the weather predictor, in the manner described in Chapters III and IV. In order to simulate somewhat realistic feedback control once the bridge is turned on, the bridge weather conditions where linearly interpolated during the 15 minute (900 second) period between 1080 seconds and 1980 seconds. This linear interpolation simulated the rate at which a real front might come into the area. The ending weather conditions were set to fairly harsh values in order to be able to show the control during the cold operating conditions for which the single heat pump simulator was designed (see Single Heat Pump discussion section above). One other peculiarity currently beyond the ability of the controller is shown in the "dip" below the 0.83 °C average bridge deck temperature setpoint that occurs at about 1800 seconds. This "dip" could easily be minimized further if the reference trajectory time constant could be set lower than five minutes, the current setting (see the Testing Methodology section above). However, as discussed previously, a lower and therefore more aggressive reference trajectory time constant tends to make ground loop flow rate steps large enough to destabilize the finite difference mathematical model included in the HVACSIM+ simulation program. Once the HVACSIM+ problem is fixed, the "dip" can and will be minimized. Notice, though, that even with the error, the average bridge deck temperature still stayed above freezing.



Bridge Site Weather Conditions		
	@ 300 seconds	@ 2040 seconds
Ambient Temperature, °C	0.5	-5
Sky Temperature, °C	1.3	-11
Wind Speed, m/s	15	15
Wind Direction, Degrees from North	60	60
Precipitation Rate, mm/hr water equivalent	5	5
Solar Radiation, kW/m^2	0	0

Figure 6.13 - Incoming Cold Weather Front Simulation

Conclusion

The model-based algorithms tested performed the best when trying to control the average bridge deck temperature for the "virtual" SmartBridge modeled by the HVACSIM+ finite-difference heat transfer model. The best performance was obtained by the Smith Predictor Controller, with the Dahlin's Controller a close contender.

By utilizing the Smith Predictor, the results show that it is possible to enjoy significant performance gains over a standard PI controller designed with ITAE design rules. This performance increase will add to the process objectives of maintaining bridge deck safety by reducing the possibility of ice, while minimizing the amount of energy wasted in the process.

Finally, by looking at the magnitude of the response times shown in Table 6.2, it is hard to believe that a structure with the thermal mass of a concrete bridge could be heated from below freezing to 0.833 ^{o}C in six minutes. This is obviously an error in the HVACSIM+ bridge simulation software. While this problem has been brought to the attention of the HVACSIM+ developers, it has yet to be isolated and corrected. Additional field tests using scale models of the bridge deck will be done to verify the time constants extracted from any future HVACSIM+ simulation. This change will definitely impact the design parameters for the controllers. However, the procedure described above can be used to derive and evaluate new models if and when the time constant problem has been corrected.

CHAPTER VII

CONCLUSIONS AND RECOMMENDATIONS

The goal of this thesis was to develop and simulate a control system for a geothermal heat pump-based bridge deck heating system. This goal was achieved by utilizing a weather predictor, utilizing weather data configured in a Multiple Independent Predictors (MIP) framework. A feedback controller, used to both provide regulatory control and to transition from a cold bridge (heat pump turned off) to a heated bridge condition, was designed and proven to work effectively. Therefore, if a heat pump based system can be designed in a cost efficient manner, the control system designed in this work will be able to maintain bridge safety in icy conditions. In addition, the control system would decrease the total bridge operating time over the course of a winter when compared to a heating system that is manually controlled, therefore reducing operating costs.

The benefits of the control system developed by this work are:

- Automatic Control of Heat-Pump Heated Bridge IS Feasible
- Motorist Safety NOT Compromised by Control System
- Control System DECREASES operating costs over manual operation

Recommendations

There are several topics stemming from this work that demand further attention. The two most important issues concern precipitation forecasting, and multiple heat pump usage.

The major assumption associated with modeling the weather prediction section of the control system was that the bridge needed to be operating, at the least, whenever the ambient temperature at the bridge site was below freezing. This does not necessarily need to be the case, however. When there is no precipitation falling onto the road surface, and no accumulation is present, a cold road surface poses no motorist safety hazard. The hazard only exists when the bridge becomes slick from freezing precipitation. Therefore, a rule could be set that the bridge only turns on when there is either precipitation falling on the bridge, or precipitation is forecasted for the area in the near future. The problem that currently exists, however, is that the Mesonet weather stations used in this study are unable to accurately measure frozen precipitation. The weather stations only register liquid precipitation. So, it is impossible to measure or predict such occurrences accurately. However, if commercial or government radar data used by meteorologists could be accessed and interpreted, a rough precipitation forecast could be generated independently of the Mesonet. Then, the bridge heating system could be turned off whenever precipitation is unlikely. This would dramatically reduce the amount of time that the bridge would need to be operating, therefore decreasing operating costs.

One of the major constraints of the feedback control system was the ability to model only one heat pump. Since a heat pump can only maintain the bridge deck setpoint of 0.83 ^{o}C under a narrow range of weather and operating conditions, this means that the heat pump is either over-sized (as in this study), or undersized under a majority of operating conditions. Once the ability to model multiple heat pumps in parallel serial flow arrangements is available, heat pump capacity should be added as a manipulated variable to the control system. This will provide much more stable control, and minimize the effect of a cooling ground loop fluid, as shown in Chapter VI.

Finally, some recommendations based on feedback parameter selection is appropriate. In the Chapter VI, the process control algorithms detailed in Chapter V were tested using the HVACSIM+ bridge deck simulation. In many cases, selection of parameters resembles more or an art than a science. As in all control decisions, good judgement needs to be used. However, a few general criterion should be set to guide this process:

1) Bridge response delay will be unavoidable, error on the side of caution (allow more time for delay). Therefore, de-tuning the parameters may be necessary.
2) Large moves (magnitude to be determined in the next Chapter) in the Ground Loop Flow Rate should be avoided. This will minimize the possibility for instabilities in the simulation software.

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