EVALUATION OF TRAILER THERMAL ENVIRONMENT DURING COMMERCIAL SWINE TRANSPORT

BY

YIJIE XIONG

THESIS

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Advisors:

Assistant Professor Angela R. Green
Professor Richard S. Gates

ABSTRACT

Transport is a critical factor affecting swine welfare in modern U.S. commercial pork production. Broad temperature ranges encountered during transport can challenge pig welfare and have been shown to increase the number of dead or down pigs following transport. Despite the general understanding of the relation between challenging transport conditions and pig welfare, little quantitative data exist which document conditions within transport trailers.

To better characterize the thermal environments experienced by trailered pigs during hot, mild, and cold weather, The National Pork Board commissioned this observational study to evaluate the thermal environment during commercial pig transport when the trailer environment was managed according to a set of industry guidelines. ***The overall goal of this observational study was to identify weather conditions and micro-climates within the trailer that created thermal challenges for the pigs.***

In this study, 84 temperature sensors were placed across trailer cross-sections in six evenly distributed zones within the transport trailer to measure air temperature experienced by the pigs. Six relative humidity and temperature probes were installed on the central ceiling of each zone to measure a representative moist-air state point for each compartment. Eighteen to twenty-four floor temperature sensors were placed onto the trailer floor prior to each monitoring trip to measure trailer floor/bedding temperature.

Transport thermal environment data from forty-three monitoring trips were collected from May 2012 to February 2013, with trailer management conducted by a commercial hauler following the National Pork Checkoff Transport Quality Assurance (TQA) guidelines. The thermal environment profile within the trailer was used to evaluate the thermal conditions to which pigs were exposed over a broad range of outside conditions [-14 to 38°C (7 to 100°F)] encountered over the four seasons of this study.

Results indicate that for outside temperature below -7 (20°F) and above 32°C (90°F) , pigs experienced extreme thermal conditions inside at least some portions of the trailer when managed according to current TQA guidelines. The ventilation patterns inside the trailer did not follow the same trend for all monitoring trips, revealing a potential to manipulate ventilation patterns with trailer management strategies. This approach for improving the thermal extremes needs further exploration.

The effectiveness of fans and misting for cooling the pigs was critically impacted by the location and coverage areas of the spray nozzles and fans. When outside temperature ranged from 10 to 20°C (50-68°F), trailer environment was within acceptable thermal limits without misting the pigs.

During cold weather, frozen floor conditions were observed, with floor temperature as cold as -20°C (-4°F) recorded in some areas of the trailer. No evidence was found to suggest that bedding depth had a measurable effect on the thermal comfort of the pigs, and its presence might increase the severity and likelihood for the pigs to be loaded onto freezing or frozen bedding in extreme cold weather.

Our data revealed no critical problems with boarding level recommendations based on current TQA guidelines, but indicated that industry guidelines could be modified to offer greater flexibility for drivers for boarding and bedding.

Keywords: swine transport, market-weight pigs, trailer thermal environment, industry recommendation, alternative practices

To my family

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I would like to extend my thanks to all of the people who helped me through my research and supported me to finish this achievement.

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CHAPTER 1. INTRODUCTION AND LITERATURE REVIEW

1.1 Current Pork Industry and Swine Transportation in the United States and the World

At a global perspective, the pork industry is the largest single sector in livestock and poultry production (USDA, 2013). It is important to the nutrition of the growing world population, and its supply chain provides an important economic impact on the world's gross domestic product (USDA, 2013).

1.1.1 Current Pork Consumption in the United States and the World

According to USDA Foreign Agricultural Services, pork is the most widely consumed meat in the world. Based on a recent world market and trade report (USDA, 2013), the world's total pork consumption in 2012 was 104,929 metric tons, while the total consumption for beef and broilers were 57,527 and 90,049 metric tons, respectively. Pork constituted 43% of the total meat consumed worldwide in 2012, while broiler chicken and turkey constituted 35%, and beef constituted the remaining 22% (Figure 1-1, USDA, 2013). For the U.S. livestock market, pork is not the most prevalent meat consumed, but it nonetheless constitutes a substantial portion of the U.S. market. In 2012, the total U.S. pork consumption was 8438 metric tons, while the U.S. consumption for beef and broilers were 11,744 and 13,342 metric tons, respectively (USDA, 2013).

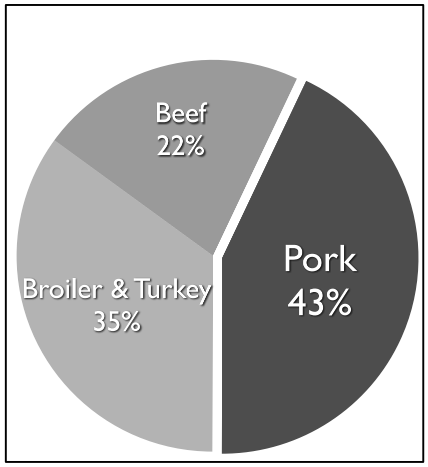

Figure 1-1. The estimation of world's total consumption of pork, beef, broiler chicken and turkey in 2013. Figure reproduced from *USDA Foreign Agricultural Services, Livestock and Poultry: World Markets and Trade Report, April 2013*.

1.1.2 Current Pork Production in the United States and the World

Global pork production has been increasing in recent years and has held at a stable level in the US (Figure 1-2, USDA, 2013). In the past five years, the world's total pork production grew about 6.7%, increasing by 6.8 million metric tons, and reached a new record of about 107.4 million metric tons. U.S. pork production stayed at approximately the same level of 10 million metric tons, and was projected to be about 10% of world's total pork production.

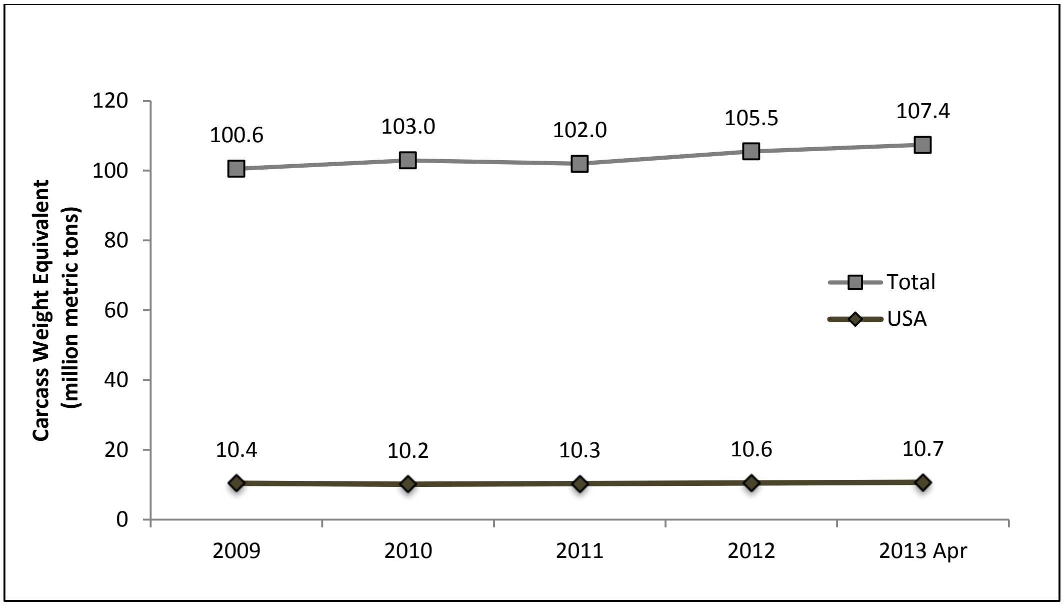

Figure 1-2. Trends of world and United States pork production from 2009 to April 2013. The world total pork production increased by 6.8 million metric tons, while the pork production of the United States stayed approximately the same. Figure reproduced from *USDA Foreign Agricultural Services, Livestock and Poultry: World Markets and Trade Report, April 2013*.

According to the latest data from national and international agencies, it is possible that the world's total pork production could increase by an additional 14 million metric tons by the year 2021, and optimistically could reach a total production of 155 million metric tons by the year 2030 (Pig International, 2013).

1.1.3 Current Swine Industry and Transportation in the United States

The regions of the United States with swine production have expanded over recent decades resulting in greater production and need for transportation. Historically, the majority of swine operations were located in the upper Midwest area (NPB, 2009). However, by 1990, North Carolina, the Oklahoma-Texas Panhandle region and Utah began developing more pork production; and by 1997, the majority of swine operations were concentrated in Iowa, Minnesota, Oklahoma, Texas, Kansas, Colorado and Utah (NPB, 2009). From 2002 to 2007, the total number of pigs increased by 7.4 million head and resulted in a total number of 67.8 million pigs in 2008, with 65,640 swine operations functioning in the United States. Iowa, North Carolina and Minnesota were the top three states with the largest number of swine inventories (NASS, 2008).

An estimated 200 million pigs are transported in the USA every year, and trips may vary from across the farm to across the country (NPB, 2008). Pigs may experience short-distance transport between swine barns within the same operation as they reach different growth stages, and mid- or long-distance transport between the swine barns and the abattoir. Pigs in the U.S typically experience two long-distance road transports in their entire life, occurring when they are transported to swine barns for the wean-stage and to the abattoir when they reach market weight [typically around 120 kg (260 pounds)]. The conditions under which pigs are transported can have a direct impact on their well-being.

1.2 Current Trailer Design in the U.S. Pork Industry

Currently, there are no standard configurations for commercial swine trailers in the United States. Trailers could be built with owner specified options (i.e. the height of the floors in the trailer, the extension of walking ramps, the placement and functionality of hinged gates, and addition of interior lighting, etc.), in addition to common features offered by the manufacturer. Thus, a great variety of trailer designs could exist among, and even within, pig transport companies (R. J. Reich, owner, Reich Trucking, personal communication, 2013). Achieving an optimal trailer design for thermal environment inside the trailer can be challenging, both from practical and economical perspectives, due to the wide range of weather experienced in the US (Ellis et al., 2010).

For current commercial U.S. pig transport, two trailer designs commonly used are drop center trailers (Figure 1-3a) and straight-deck trailers (Figure 1-3b) (Ritter et al., 2008a). The major difference between these two trailer designs is that the center area of the drop center trailers are lower to the ground than the front and the rear sections of the trailer.

With both trailer designs, large and small side-openings are commonly punched identically on trailers' outside surface with 21-inch side post spacing for greater strength. Small side openings allow minimum airflow inside the trailer; while larger oval openings provide more ventilation inside the trailer to better cooperate the thermal environment experienced by the animals during transport. Heavy-duty gates with full-framed aluminum construction are also employed inside the trailer to provide smooth operation and easy segregation during animal loading procedure. The side opening design for both trailer designs also retain minimal leakage, less contamination, and easy cleaning. Trailers interior volume can be divided into two levels or three levels, based on specific transport purposes.

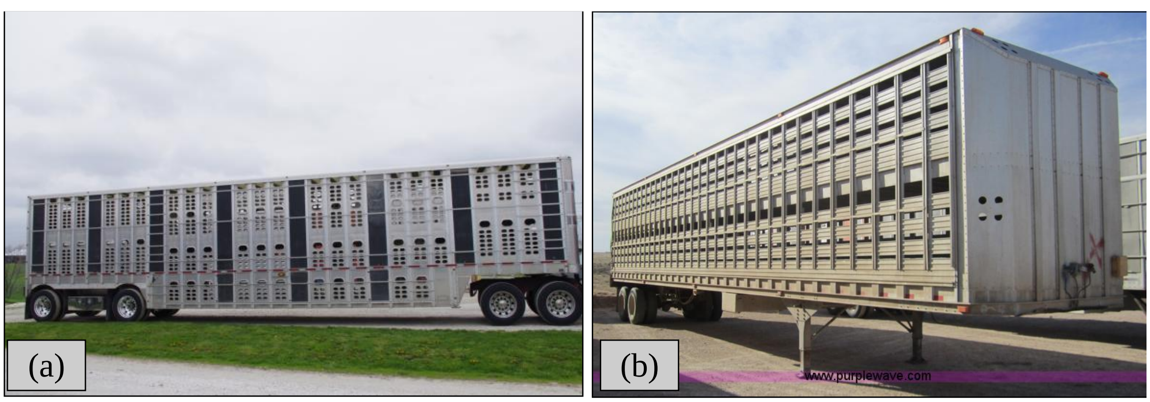

Figure 1-3. Commonly used swine transport trailer configurations in current U.S. pork industry. (a) A drop center trailer design with punched sides, also known as pot-belly trailer and (b) straight-deck trailer.

The drop center trailer, also known as a pot-belly trailer, is the most widely adopted trailer design within the Midwestern U.S This configuration allows trailer operators to divide the trailer internal volume into multiple levels and typically has punched side openings on the trailer surface for ventilation (Figure 1-3a). According to Rick Reich (personal communication, owner, Reich Trucking, August 10, 2013), the drop center trailer design maximizes vertical compartment heights inside the trailer, optimizes human safety by being more driver friendly, offers more versatility for the animals that are transported, and provides more resistance to trailer overturning. On the contrary, extra ramps inside the trailer, which challenge the animals when they have to ascend or descend during loading/unloading periods is perceived as the major disadvantage of drop center trailers.

Straight-deck trailers can be further characterized into straight-through loading trailers and shallow drop trailers. Compared to drop-center trailers, straight-deck trailers are slightly easier for transporters in the loading/unloading periods, and easier to maintain acceptable biosecurity from a cleanliness standpoint. Conversely, straight-deck trailers are less driver-friendly, mostly due to less vertical spaces inside the trailer and lower stability on the road due to a higher center of gravity.

Ellis et al. (2010) claimed that side openings should be varied according to different size, shape, and compartment locations to achieve desired airflow rate inside the trailer to maintain a reasonable thermal comfort range for the pigs. For common current trailer designs, the openings can only be covered by slot plugs and wind-slats, and typically cannot be adjusted between different levels of the trailer. Even for trailers with plug-type openings, adjustments are time-consuming and difficult for upper levels, thus not practical to change with every fluctuation of the weather.

1.3 Pig Thermoregulation, Physiology and Responses to Environmental Changes

Understanding the physiological interactions between livestock and their thermal environment may be complex, yet is critical for effectively managing production. Over the past five decades, comprehensive studies have been conducted to describe the relation between thermal environment and livestock response. Nevertheless, limited knowledge was acknowledged for practical industry management and engineering design (Bond et al., 1959; DeShazer et al., 2009).

Conventional swine housing standards based upon the relationship between pig thermoregulation and thermal environment have been developed (Bond et al., 1959), and are widely applied within pork industry. Limited studies were subsequently done to better understand the interaction between thermal environment and pig thermoregulation (Brown-Brandl et al., 1998; Harmon et al., 1997).

Knowledge of pig's thermoregulation was studied and provided by Curtis (1983), Hillman (2009) and Willmer et al. (2009). According to these studies, livestock maintain their core body temperature at a relatively constant temperature, 38°C for pigs, despite exposure to a wide range of ambient temperatures. This negative-feedback physiological control loop for maintaining constant conditions is defined as homeostasis. Environmental changes that provoke an animal's adaptive responses may be regarded as environmental stressors, such as heat stress or cold stress (Curtis, 1983; Willmer et al., 2009).

When their homeostasis status is interrupted by environmental stresses, pigs will first initialize low-energy-consuming behavioral responses, such as altering postures, huddling with other animals, seeking surrounding protection, avoiding adverse environmental factors, or otherwise altering their micro-environment to counter the thermal stressor. When such behavioral response is not adequate to establish a thermal balance, pigs will initiate more aggressive involuntary responses such as panting or shivering (Curtis, 1983; Curtis, 1985; Hillman, 2009). The level of stresses could be altered by the degrees of intensity and the duration of the stress (Curtis, 1983; Hillman, 2009). When a stressor becomes progressively more severe, negative physiological responses generated by the pigs become extreme, and potentially lead to undesirable well-being status of the pigs (Curtis, 1983; Hillman, 2009).

For pigs dealing with cold stress, physiological responses, such as shivering, metabolism, blood circulation, activity level, and huddling will be invoked. Previous studies have indicated that when pigs are exposed to an ambient temperature lower than 12°C without any other protection, the pigs are considered to encounter cold stress (Haresign et al., 1977; Baker, 2004). The extreme low temperature, which could cause lethal consequences for finishing pigs is -20°C (Curtis, 1985; DeShazer and Overhults, 1982; Holden and Ensminger, 2006; Hahn, 1985; NRC, 1981).

When dealing with heat stress, pigs initialize responses such as decreased activity levels, searching for shade, invoking peripheral vasodilation, and panting (Curtis, 1983; Hillman, 2009; Willmer, 2009). Unlike other livestock, due to lack of sweat glands on their skin surface, pigs can only lose heat from evaporative heat loss by panting (Hacker et al., 1994; Huynh et al., 2007; Morrison et al., 1967; Morrison and Mount, 1971; Turnpenny et al., 2000). For pigs, their thermoregulatory processes responding to heat stress is energy-costly as the maximum thermal panting takes as much as 15% of the energy produced by total heat production. (Curtis, 1983). Curtis (1983) claims that in response to heat stress, pigs initialize panting behavior when their skin temperature exceeds 35°C. For finishing pigs, the upper extreme temperature is about 35°C, while the lethal body temperature is about 42°C (Curtis, 1985; Curtis, 1983; DeShazer and Overhults, 1982; Hahn, 1985; Holden and Ensminger, 2006).

Compared to cold stress, heat stress has the potential to increase animal losses (Curtis, 1983, Hillman, 2009). Previous studies have shown that by challenging pig's coping ability, heat stress could result in reduced production efficiency, decreased feed intake and compromised animal welfare (Brown-Brandl et al., 1998; Brown-Brandl et al., 2001; Brown-Brandt et al., 2011; Brown-Brandt et al., 2004). Because of heat stress, an annual estimation of $299 million economic loss in pork production was reported (St-Pierre et al., 2003).

The intensity of thermal stress encountered by pigs is greatly impacted by time of exposure to the thermal stress and the level of acclimation, as pigs can be severely compromised by less extreme cold temperatures with long period exposure (Curtis, 1983; Hillman, 2009; Willmer, 2009).

Thermoneutral zone indicates the ambient temperature range within which pigs can maintain their appropriate constant core body temperature with the least thermoregulatory effort and minimal metabolic heat production, and is defined as the range between the lower end of the lower critical temperature and the upper end of the upper critical temperature [Figure 1-4, (IUPS Thermal Commission, 2001; Hillman, 2009)]. When staying within thermoneutral conditions, pigs have the potential to reach optimal performance and health status (Randall et al., 2001; Hill et al., 2004; Willmer et al., 2004).

Previous studies have indicated that the thermoneutral zone for finishing pigs (weighing between 70 to 100 kg) could range from 10 to 25°C, and this temperature range is widely applied in agricultural research relating to swine (Curtis, 1985; DeShazer and Overhults, 1982; Holden and Ensminger, 2006; Hahn, 1985; Morrow-Tesch et al., 1994; NRC, 1981). Due to developments and changes in genetic, generation, and environment, the thermoneutral zone for finishing pigs have been modified to 18 to 28°C (Brück and Zeisberger, 1978; Brown-Brandl et al., 2001; Brown-Brandl et al., 2013; Collin et al., 2001a; Curtis, 1985; Quiniou et al., 2001).

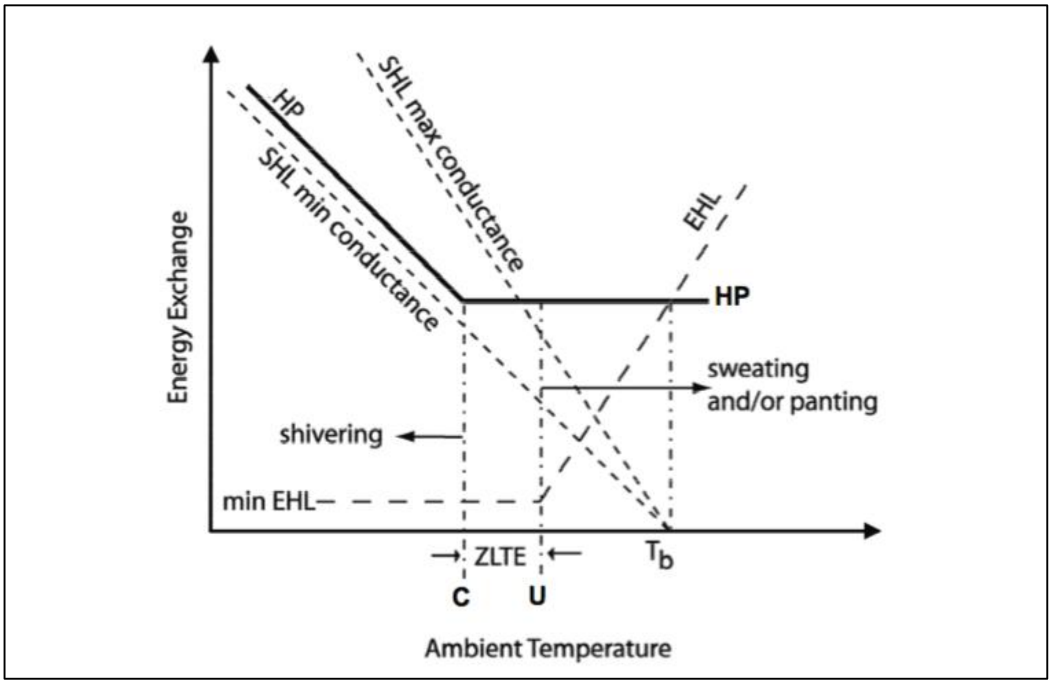

Figure 1-4. The zone of least thermoregulatory effort (ZLTE) is bounded by the lower critical temperature (C) where conductance is minimum and metabolic heat production (HP) increases with falling temperatures and by the evaporative critical temperature (U) where conductance is at its maximum and the onset of rising evaporative heat loss (EHL) begins with sweating, panting or both. The upper critical temperature as defined by IUPS Thermal Commission (2001) is synonymous with evaporative critical temperature presented by Black et al (1986). Tb = deep body temperature, SHL = sensible heat loss. Reproduced from Hillman (2009).

1.4 Environmental Measurements, Thermal Indices and Their Implications for Livestock Environments

Many factors, including animal species, genetics, and nutrition level can influence the animal's coping ability to the environmental conditions they encounter. Environmental factors that directly influence an animal's thermal exchange process may include surrounding surface temperature, air temperature, air velocity, air vapor pressure, surrounding shape factor for radiation, emissivity of surrounding surface, thermal resistance of contact surface, heat capacity of contact materials, etc. (Hahn, 1976; Eigenberg et al., 2009). Weather condition, as well as the trailer design will also affect the heat transfer pattern between the animal and the surrounding environment (Eigenberg et al., 2009).

To measure the surrounding thermal environment encountered by livestock that influence their heat exchanges process, some most commonly adapted environmental measurements in animal agriculture may include air temperature, relative humidity, radiation, and air movement (Cox, 1997; Hahn, 1985; Eigenberg et al., 2009).

1.4.1 Environmental Measurements

Air temperature is the most commonly used and an easily attained measure to assess thermal conditions. Eigenberg et al. (2009) claimed that in a barn, ventilation patterns, wind, and undesirable openings will create a significant difference in the air temperature at the caretaker height and the animal levels, which also likely applies to transport trailers. To measure the air temperature best describing the thermal environment experienced by the animal, Eigenberg et al. (2009) and Green et al. (2009) suggested that the sensors should be located as close to the animal level as safely possible. As a practical matter, temperature sensors, such as expansion types (i.e. thermometer), thermocouples, and electrical resistance types (i.e. thermistors) are most commonly applied in air temperature measurements in agriculture and horticulture (Cox, 1997).

Hahn (1976) claimed that air temperature only directly affects the convective heat loss of the animal, and can be altered by many other factors. In order to make effective and efficient management, more environmental parameters need to be included to accurately represent the total heat exchanges between the animals and the thermal environment they experienced (Eigenberg et al., 2009).

Surrounding surface temperature indicates the floor or surface temperature in which the animals are in contact. Previous studies have shown that implementing a cooled or heated floor can alter conductive heat loss and sensible heat production (Spillman and Hinkle, 1971; Restrepo et al., 1977; Vacha and DeShazer, 1983; Eigenberg et al., 2009). By studying different floor temperature effects on the conductive heat losses of grow-to-finish pigs, Restrepo et al. (1977) reported that the conductive heat loss of the studied pigs decreased when the floor temperature changed from 20, 15, to 10°C or increased from 25, 30 to 35°C. Vacha and DeShazer (1983) confirmed Restrepo's finding noting that a reduction in sensible heat was observed for increased floor temperature at a given air temperature range. Results of these studies have recognized an important need for the consideration of floor or surface temperature. According to the National Pork Board trailer management guidelines, increased evaporate cooling of the pigs can be achieved by adding more moisture to the bedding materials during transport, in hot conditions (NPB, 2008).

Mean radiant temperature (MRT) is another indicator of the animal thermal environment. Defined in the ASHRAE Handbook of Fundamentals (2004), MRT is measured as the uniform temperature of a black enclosure that results in the same heat loss by radiation from the animal as from the actual enclosure. To measure the MRT, Bond and Kelly (1955) developed a globe painted flat black instrumentation, with globe temperature, air temperature and air velocity employed. Other commonly used sensors for MRT measurements include Eppley pyranometer and silicon photodiode pyranometer sensors (Cox, 1997; Eigenberg et al., 2009).

Air velocity greatly influences an animal's convective heat losses. By increasing the air velocity around the animals, undesirable consequences due to hot conditions can be mitigated (Curtis, 1983, Eigenberg et al., 2009). On the other hand, animals can be chilled if an increase in air velocity is added to cold environments. Increasing air velocity can effectively result in an increase in both the upper critical temperature and the lower critical temperature of the animal (Curtis, 1983, Eigenberg et al., 2009). Understanding air velocity in the animal environment is an important tool to understand the ventilation patterns in a space, and to aid in management of the thermal environment (Eigenberg et al., 2009). Air speed can be measured by various anemometer designs, including rotational, pressure, deflection, thermoelectric, and Doppler anemometers (Eigenberg et al., 2009; Cox, 1997).

Defined in the ASHRAE Handbook of Fundamentals (2001), relative humidity indicates the ratio of the partial pressure of water vapor in a space to the partial pressure of water vapor in the space at saturation. In short, it is a relative measure of the degree of moisture saturation of the air. Relative humidity is a useful parameter for effective and efficient management in the thermal environmental measurements relating to animal environmental management (Cox, 1997). Undesirable relative humidity can greatly impact the thermal comfort, well-being, performance, disease, and mortality (Lowen et al., 2007; Huynh et al., 2005b). Lenkaitis (2007), Ritter et al. (2006), Stull (1999) reported relative humidity as high as 100% during market weight pigs and horse road transport.

Many types of sensors are widely applied to measure the relative humidity, including wet-bulb psychrometer, surface acoustic wave sensor, substrate or polymer-based sensor, lithium chloride-based sensors, thermal conductivity sensors, and infrared absorption hygrometer (Cox, 1997; Eigenberg et al., 2009).

1.4.2 THI and its Application for Livestock Environments

Thermal indices, such as temperature humidity index (THI), combine multiple thermal parameters into a single quantifiable measure for assessing thermal environments. This approach improves upon the single measures by considering additional heat losses and gains beyond those measured by simple air temperature (Hahn et al., 2009; Hahn, 1995; Hahn and McQuigg, 1967). Current development of thermal indices has focused on moderate high temperature conditions to help in reducing the risks of animal losses due to temperature extremes in hot weather (Hahn et al., 2009).

As air temperature alone cannot represent the thermal environment assertively, more environmental measures are combined with air temperature measurement to represent the effect produced by the heat exchanges between the animals and the thermal environment (Hahn et al., 2009).

The measurement of THI was initially developed by Thom (1959) and was used to indicate the discomfort index for human, and it then has been extensively applied in current agricultural management and production. Previous studies have shown that the combined effects of air temperature and relative humidity better represent the animal's ability to thermoregulate, thus the measurement of THI index is considered to be an important representation of the overall thermal impact on livestock, especially in moderate and hot conditions (Brown-Brandl et al., 1997; Hahn et al., 2009; Hahn, 1995; St-Pierre et al., 2003). For many years, THI has been adopted as a classification standard of the thermal environments, and has been widely applied in various areas, including animal production, animal transportation, and animal housing, to make rational and effective management decisions during hot conditions (Hahn et al., 2009).

THI calculations vary by species, giving more or less weight to measures of moisture based on the animal's susceptibility to high humidity. For pigs, THI can be calculated from the following equations, where dry-bulb temperature (T_{db}), wet-bulb temperature (T_{wb}), and dew-point temperature (T_{dp}) are °C, and relative humidity (RH) is % (Hahn et al., 2009):

$$THI = 0.72(T_{db} + T_{wb}) + 40.6 \qquad \text{(Equation 1-1)}$$

$$THI = T_{db} + 0.36 \times T_{dp} + 41.2 \qquad \text{(Equation 1-2)}$$

$$THI = 0.8T_{db} + RH(T_{db} - 14.4) + 46.4 \qquad \text{(Equation 1-3)}$$

THI values have also been adopted to set the Livestock Weather Safety Index (LWSI) ranges to represent heat stress categories encountered by livestock during hot-weather conditions. (LCI, 1970). In current agricultural application, the LWSI categories were specified by cattle and have been extensively applied in other livestock managements (Hahn et al., 2009; Hahn and Mader, 1997; Hubbard et al., 1999). Nevertheless, limited information of the application of the LWSI categories on swine industry was practically provided, due to the complexity and lack of corresponding thermal index development (Hahn et al., 2009).

1.5 Transport Effects on Pig Well-being

Road transportation is essential in the pork production cycle, but is considered one of the most influential factors that affect pig well-being. Transport has been linked with animal condition, transport losses and final pork quality (Benjamin et al., 2001; Berry et al., 2009; Ellis and Ritter, 2006; Mitchell et al., 2004; Ellis and Ritter, 2005; Ritter et al., 2009a; Sutherland et al., 2009c). An estimated 200 million pigs are transported annually in commercial over-the-road vehicles in the U.S., with approximately 500,000 pigs (0.25%) reported as down or dead on arrival (DOA) (FSIS, 2007, 2008, 2009). One study reported 70% of deaths occurred during transport and 30% died shortly after arrival (Lenkaitis et al., 2008). Almost 60,000 pigs are reported to experience non-fatal stress and negative welfare conditions (i.e. down but not dead) during transport (Benjamin, 2005). This creates a great economic loss and a serious welfare concern to the U.S. pork industry (Speer et al., 2001). Even though the annual DOA rate has decreased from 0.22% to 0.15% over the past eight years, the U.S. pork industry still experiences an estimated $46 million economic loss each year (Ritter et al., 2009a).

During transport, pigs experience many novel factors including vibration, noises, trailer speed changes and potential weather extremes. These factors challenge the pigs' coping abilities and can become the most stressful event during a pig's whole life (Green, 2011). Other significant variables that impact the pig's well-being status during transportation include: space allowance and loading density (Sutherland et al., 2009b; Sutherland et al., 2009c), transport durations (Bryer et al., 2011), trailer design (Brown et al., 2011; Ritter et al., 2008a; Kettlewell et al., 2001c), handling methods (McGlone et al., 2004), and trailer management (Ritter et al., 2008b; Ritter et al., 2009b; Ellis et al., 2010; Sutherland et al., 2009a). Heat stress, cold stress, and reduced air quality are reported challenges for maintaining thermally acceptable conditions for pigs during transport (Kojima et al., 2008; Ivers et al., 2002; Fitzgerald et al., 2009). Failure to maintain an appropriate thermal environment range during transport can result in increased mortality, decreased product quality, reduced overall production efficiency and compromised animal welfare (Benjamin, 2005; Ellis and Ritter, 2005; Pilcher et al., 2011; Sutherland et al., 2009c).

1.5.1 Space Allowance

Space allowance, or loading density on the trailer could potentially influence both behavioral and physiological responses of the pigs during transport. Many studies have been conducted on market weight finisher pigs to assess the effects of space allowance on pig well-being during transport (Sutherland et al., 2009c; Warriss, 1998). Studies have shown that higher loading density associates with greater in-transit losses (Warriss, 1998; Ritter et al., 2009b), reduced behavioral responses (Sutherland et al., 2009c), and jeopardized stress and fatigue level (Sutherland et al., 2009b; Warriss, 1998). Ritter et al. (2006) reported that with an increase in in-transit floor space from 0.39 to 0.48 m^2/pig, the percentage of total non-ambulatory, injured (NAI) pigs, non-ambulatory and non-injured (NANI) finished pigs and total in-transit losses reduced from 0.62 to 0.27%, 0.52 to 0.15%, and 0.88 to 0.36%, respectively. Similarly, Haley et al. (2010) evaluated the space allowance effects on in-transit loss for finishing-pigs and reported over twice as many in-transit losses space allowances between 0.43 and 0.44 m^2/pig, compared with space allowance above 0.52 m^2/pig.

1.5.2 Transport Duration

Previous studies have indicated that transport duration is a significant influential factor affecting pig well-being. Sutherland et al. (2009a) and Ritter et al. (2009a) demonstrated that swine transportation could be further categorized into short duration transport (≤ 3 hr) and long duration transport (> 3 hr). Their results have indicated that short duration transport has a greater occurrence of mortality and more down pigs than long duration transport, and greater mortality and DOA rate were reported during the first hour of transport. The most plausible reason for this consequence is that pigs do not have enough time to recover from one stressor (loading) before the next stressor is applied (unloading). If an extreme thermal environment is additionally encountered as heat or cold exposure during the loading process, adverse effects may be compounded (Curtis, 1985). Rademacher and Davies (2005) observed the highest mortality rate of pigs occurred in the first 30 to 90 minutes in transport. Sutherland et al. (2009a) found that transportation less than 3 to 4 hr in duration reveals the highest DOA rate at the abattoir of the pigs. Bryer et al. (2011) reported that road transportation could result in undesirable physiological responses among pigs, such as dehydration and deprivation after transport, regardless of transport durations.

1.5.3 Trailer Design

There are no standard configurations for commercial swine trailer design in the current pork industry. Trailer design could be a potential factor that influences the thermal environment and ventilation pattern of the trailer, which could eventually reduce pig performance and increase transport losses (Dalla Costa et al., 2007). Warriss et al. (1991) and Ritter et al. (2008a) reported that more internal ramps in pot-belly trailers make a major difference between the two trailer designs, and could create more difficulties for the pigs during loading and unloading procedures. In previous studies, Ritter et al. (2008a) evaluated the effects of two conventional trailer designs (pot-belly vs. straight-deck) on physical indicators of stress of the pigs, including open-mouth breathing, skin discoloration and muscle tremors. They found that pigs on pot-belly trailers experienced greater physical stress levels during unloading period than straight-deck trailers, but trailer design had minimal effects on total transport losses. Ellis et al. (2010) reported that higher CO_2 concentrations and temperatures were observed toward the front of a straight-deck trailer, which indicated a lower ventilation rate in the front of the trailer compared to the rear. A similar study was conducted under eastern and western Canada climates with two different trailer designs (pot-belly vs. straight-deck) by Brown et al. (2011). They found a similar thermal distribution trend inside the trailer, of which the thermal environmental measurements (temperature and relative humidity) and ventilation patterns inside the trailer varied significantly between different compartments of the trailer.

1.5.4 Handling Intensity

Handling intensity and handling methods vary among pig producers and transport handlers, and handling tools to aid in interactions with the pigs vary as well. No formal regulations have been applied to control the handling intensity and handling methods in current U.S. swine transport procedure, however, handling is a significant concern from an animal welfare perspective. Previous studies have indicated that handling intensity greatly impacts the number of non-ambulatory pigs at arrival at the abattoir (Benjamin et al., 2001; McGlone et al., 2004; Ritter et al., 2009a). Benjamin et al. (2001) and Hamilton et al. (2004) found that additive effects on physiological responses, including increased heart rates, rectal temperatures, blood glucose, reduced blood pH, and bicarbonate were observed in pigs that were aggressively treated with electric prods, compared to pigs that were more gently handled (for example, with a sorting panel or a shaker paddle). Ritter et al. (2009b) assessed the effects of handling intensity (aggressive vs. gentle) on pigs' physiological responses prior to transport. In their study, handling intensity was categorized by the number of shocks from an electric prod, of which “gentle” indicated 0 shocks while "aggressive" indicated 8 shocks. Results showed that the metabolic stress response level greatly increased when pigs were handled aggressively before transport.

1.5.5 Thermal Environment

Previous studies have indicated that when animals are experiencing potential extreme environmental conditions that exceed the threshold limit, their health and performance can be jeopardized (Brown-Brandl et al., 1998; Collin et al., 2001b; Curtis, 1985; Curtis, 1983; Hillman, 2009; Huynh et al., 2005a). If the animal cannot reestablish homeostasis by regulating their physiological and immunological systems, the extreme environment can lead to reduced performance, health and well-being of the animal, or even death (Curtis, 1983; Hillman, 2009). Kettlewell et al. (2001a) stated that the micro-environment experienced by the animals greatly impacts their thermoregulatory processes, thus creating challenges in their ability to cope with environmental stressors during transport. The thermal micro-environment has been perceived to be the major stressor that affects chicken well-being during transport (Mitchell and Kettlewell, 1998), and the same is likely to be true in pig transportation. The thermal environment in typical U.S. commercial transport trailers is not actively controlled, and is affected by a number of factors, including external temperature, ventilation rate, occupant contribution to thermal load and spatial density, trailer design and transport duration (Brown et al., 2011; Warriss, 1998; Purswell et al., 2006; Ritter et al., 2009a). Haley et al. (2010) reported that external environment is more critical than space allowance on in-transit loss as they observed in-transit loss to increase by 6.6 times at temperatures between 28^{o}C and 34^{o}C. Ellis et al. (2010) found that when the trailer was stationary during loading or waiting at the plant prior to unloading, greatest temperature extremes inside the trailer was observed, which created greater incidence of occurrence of thermal stress that experienced by pigs.

1.5.6 Trailer Management

Previous studies have indicated that the rates of downed animals increase as the ambient environmental conditions move toward extreme cold or hot (Ritter et al., 2008b; Ritter et al., 2009b; Ellis et al., 2010; Sutherland et al., 2009a).

Limiting the occurrence of poor thermal environments during transport is challenging, because current trailer designs provide limited opportunity for modifying trailer temperature, humidity, air velocity or air quality. To address this challenge, Transport Quality Assurance (TQA), an industry certified program was developed by the National Pork Board to provide the industry with information of handling equipment, handling techniques, and the potential impact of these implications on pig well-being status during transport (NPB, 2008). Currently, TQA program is widely used by commercial trucking companies, pig producers and pig handlers. The goal of applying the TQA program is to ensure the transported pigs receive proper handling and a high standard of trailer management.

The TQA management repertoire includes trailer boarding (amount of opening along the trailer) that limits flow of cold air into the trailer and bedding (presence and depth of a substrate such as wood shavings) that is provides potential insulative effects for the pigs during cold weather and increases footing for the pigs while moving into and out of the trailer (Table 1-1).

Table 1-1. Transport Quality Assurance guidelines for truck setup procedures during temperature extremes for market pigs (source: TQA handbook, 2008).

Ambient Temperature (°C)	Bedding	Boarding (side-slats)	
< -12	Heavy	90 % Closed	10% Open *
-12 ~ -6	Medium	75% Closed	25% Open *
-7 ~ 3	Medium	50 % Closed	50% Open
4 ~ 9	Light	25% Closed	75% Open
> 10	Light**	0 % Closed	100 % Open

* Minimum openings are needed for ventilation even in the coldest weather.

** Consider using wet bedding if it is not too humid and trucks are moving.

Based on data derived from the National Pork Board (NPB), the application of TQA has significantly reduced the number of pig losses and fatigued pigs at arrival at harvesting facilities. Moreover, pork quality affected by improper handling methods during transport procedure has also been reduced. However, the implementation of these practices varies among producers.

The evaluation and management of temperature and humidity in the trailer has previously been explored for variations in the macro-environment [ie.using single measures taken near the ceiling within the various compartments within the trailer (Lenkaitis et al., 2008)]. These central measures do not account for the potential variability within the trailer, and micro-environment and distributions near pig level may have a significant impact on individual animals. While industry recommendations for bedding, boarding and misting are offered through the TQA program, these recommendations are based largely on experiential information rather than scientific data. Thus there is a critical need to further understand and improve the management of the transport environment during extreme weather events.

CHAPTER 2. THESIS OBJECTIVES

To better characterize the micro-environment experienced by trailered pigs managed under the TQA guidelines during hot, mild, and cold weather, The National Pork Board commissioned a study (Green, 2011) for which an instrumentation system was designed and implemented into a new commercial swine transport trailer (Xiong et al., 2012). This thesis addresses three objectives of that study:

1. To characterize the thermal environment inside a swine trailer operating under current TQA management guidelines over a broad range of outside temperatures.

2. To assess current TQA management guidelines for hot weather conditions, including misting and fan operation for market-weight pig transport.

3. To assess current TQA management guidelines for cold weather conditions, including bedding and boarding managements for market-weight pig transport.

4. To assess alternative boarding management practices for cold weather conditions for market-weight pig transport.

CHAPTER 3. MATERIALS AND METHODS

3.1 Trailer Description

A newly fabricated commercial swine trailer (Model No.PSDCL-420P with customer-selected customization, Wilson Trailer Company, Sioux City, IA) with a loading capacity of 34,020 kg was used. The trailer overall dimensions were 15.84 m long × 2.52 m wide ×2.50 m high (Figure 3-1). The internal space of the trailer was divided into two levels, and on each level, the space was further divided into 3 zones numbered from 1 to 3 (from the front to the back of the trailer on the top level), and 4 to 6 (from the front to the back of the trailer on the bottom level) to identify positions in the trailer (Figure 3-2). The same driver operated the truck and trailer, and managed the animals and trailer configurations according to TQA guidelines during all transport throughout the study.

Figure 3-1. Trailer for observational field study. The same trailer was instrumented and utilized for all monitoring of pig micro-environment during all transport throughout this study.

As shown in Figure 3-2, the numbered zones are divided with hinged gates to separate the pigs into groups during transport. For the central zone on top and bottom levels, the monitoring equipment was located to the side of the central gate so that no sensor was over the gate.

3.2 Trailer Environment Monitoring System

3.2.1 Overview

A monitoring system was developed to assess the thermal-environment inside a commercial swine transport trailer. The system consisted of equipment to measure air temperature near pig level, central air temperature and relative humidity of each zone, exposed surface temperature, and floor/bedding temperature taken in six zones of the trailer representing the upper and lower levels and the front, center, and rear of each.

A summary of the instrumentation used in the system is presented in Table 3-1. The placement of each sensor within the trailer is demonstrated in Figure 3-2. The data acquisition center was located at the rear zone (Zone 3) on the top level of the trailer, also called the doghouse (Figure 3-2b).

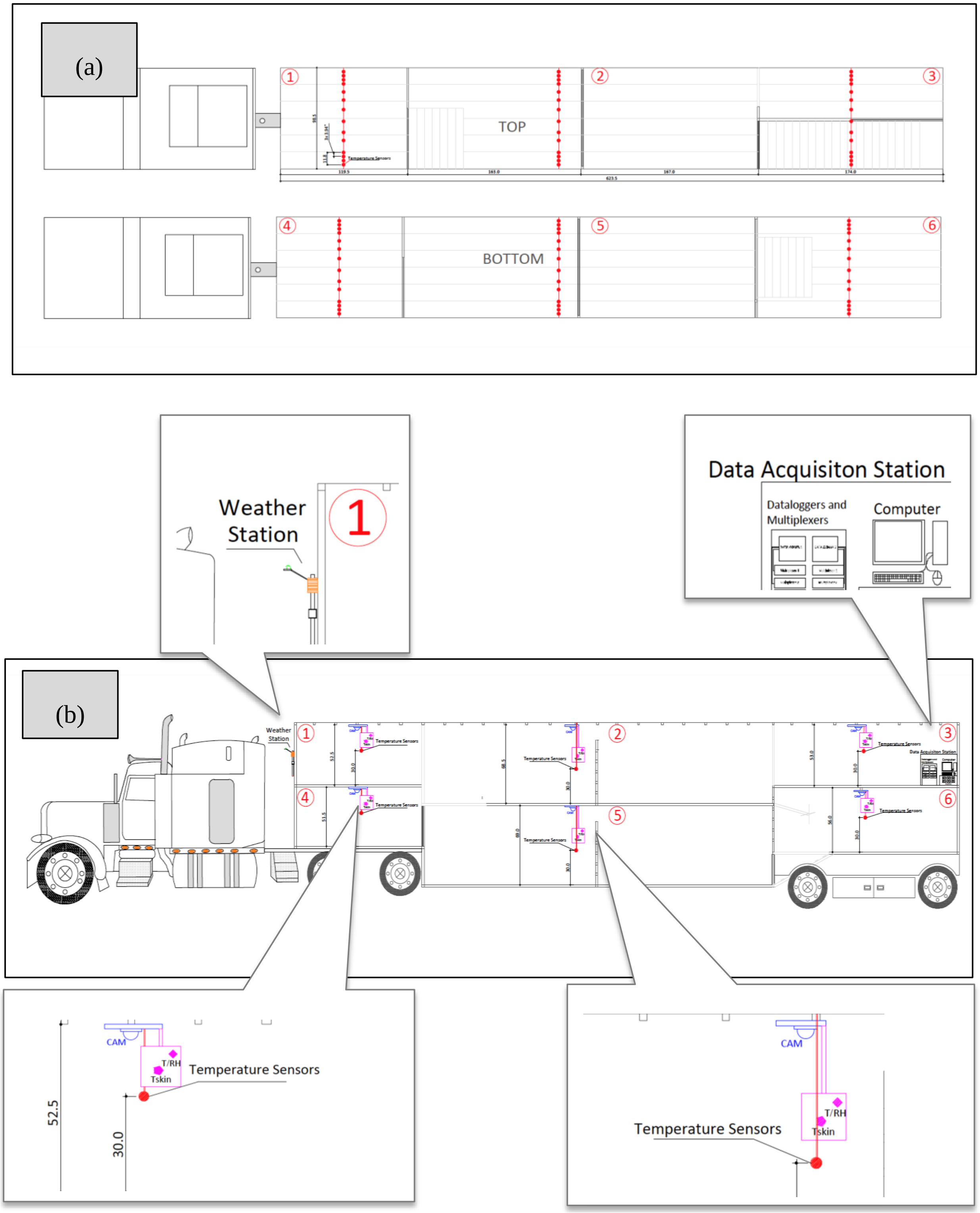

Figure 3-2. Trailer Schematics. (a) Top zone and bottom plan view of the trailer, to illustrate the horizontal distribution of sensors in each zone and (b) the left-side elevation view of the six zones and illustrates the vertical distribution of sensors used to capture air temperature, skin temperature, zone-centered temperature/relative humidity and floor temperature.

Table 3-1. Instrumentation summary. Environmental conditions were measured with a set of measurements to represent the micro-environment in three dimensions within the trailer by collecting zone center conditions, a cross-section of air temperature, pig exposed surface temperature, and floor temperature.

Measurement	Location	Sensor	Model, Manufacturer	Sampling Frequency
Air Temperature	Cross Section for 14 locations within each zone	Thermistor	10M5351,Honeywell	1 minute
Central Air Temperature and Relative Humidity	Central at ceiling within each zone	Humidity and Temperature Sensor	HMP60, Vaisala	1 minute
Pig Surface Temperature	Central at ceiling within each zone	Infrared Radiometer	Apogee SI-111 Campbell	1 minute
Floor/Bedding Temperature	Floor/Bedding, scattered through trailer	iButton	DS1921G-F5, Maxim	10 minutes
Datalogging	Upper rear of trailer	Datalogger	CR23X, Campbell	1 minute
External Weather Condition	Outside trailer	Remote Monitoring System	U30-NRC-SYS-B, Onset	1 minute
Trailer Speed	From cab of truck	iTrail GPS tracker	Sleuth Gear Track	10 minutes

3.2.2 System Design and Construction

The instrumentation system was designed for straightforward installation and removal during each monitoring trip. The design goals were to provide for secured data collection during each trip, simple adjustment, an unobtrusive presence during pig loading/unlaoding periods, and minimal labor for periodic monitoring over the course of a year.

3.2.2.1 *Power Supply*

Two parallel-connected 12V DC lead-acid deep cycle batteries (T-1275, Trojan Battery Company, Santa Fe Springs, CA) were used to power the instrumentation system inside the trailer to provide sufficient power supply for the instrumentation system in consecutive trips (up to 12 hr). The battery has capacity minutes of 280 minutes at 25Amps, 102 minutes at 56 Amps and 70 minutes at 75Amps. The capacity Amp-Hours (AH) of the battery is 120 AH at 5-hr rate and 150 AH at 20-hr rate, respectively. The batteries were hooked up to the truck's power in order to receive 30A of charge during transport.

3.2.2.2 *Data Acquisition Design*

The data acquisition center consisted of a personal computer, datalogger (CR 23X, Campbell Scientific, Logan, UT) and three compatible relay multiplexers [Figure 3-2b, Model AM16/32, Campbell Scientific, INC., Logan, UT]. Custom connectors were fabricated for the instruments in each section and the data acquisition center. Wires with custom-fit lengths connected instruments from each section with the data acquisition center.

3.2.2.3 *Instrumentation Construction*

The sensors were protected from environmental damage by routing within PVC pipes, with sensor height of 76 cm (30 in) above pig level and 1.2 m (48 in) above trailer floor (Figure 3-3) in all zones to avoid potential damage from the pigs. The pig level air temperature cross-sectional mounts were designed with two configurations due to two different height designs of the trailer, which are 130 cm (51.5 in) and 175 cm (69 in), respectively. For each zone within the trailer, 4 sensors distributed at closer intervals near both sides and 6 sensors evenly distributed in the middle (Figure 3-3b and Figure 3-4). In the front and rear sections (zone 1, zone 4, zone 3, and zone 6), the PVC pipes were mounted along the ceiling in the middle of each compartment with heavy-duty zip wires and self-screws. The sensors were hanging downward with the protections from 14 PVC caps (Figure 3-3a). In the middle zones (zone 2 and zone 5), the sensor mount was affixed to the ceiling and extenders were added to the PVC pipe, and sensor wiring was protected by flex conduits (Figure 3-3b).

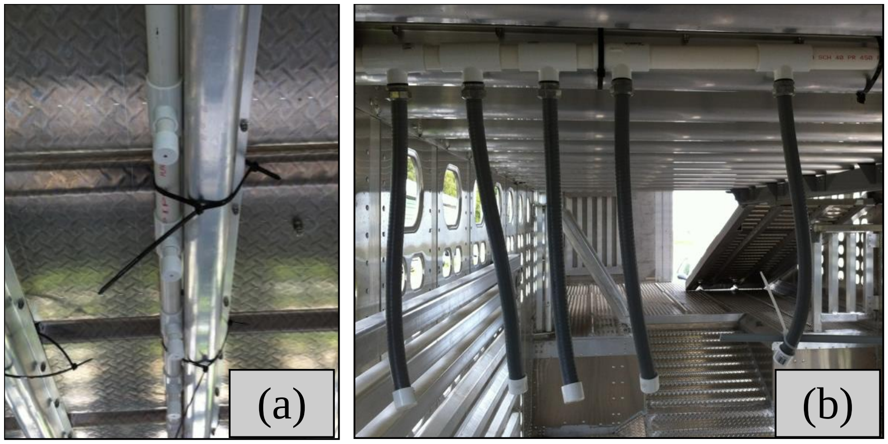

Figure 3-3. Mounted PVC pipes for thermistors in trailer. (a) Mounted PVC on ceiling in front and rear zones, and (b) the PVC pipes fixed on the ceiling with 14 flex conduits hanging down. The vertical placement with respect to the height above the pigs' back was consistent for all zones within the trailer.

A custom-designed and fabricated instrumentation board (Figure 3-4a) was located at the central ceiling area in each zone. The central instrumentation board consisted of one connection box for thermistor sensors, one zone-centered air temperature and relative humidity probe, one exposed skin surface temperature sensor, and video camera for documentation for further research (Figure 3-4b). A custom-fabricated metal mesh cage was affixed to the instrumentation board to protect the sensors from potential damage from the pigs.

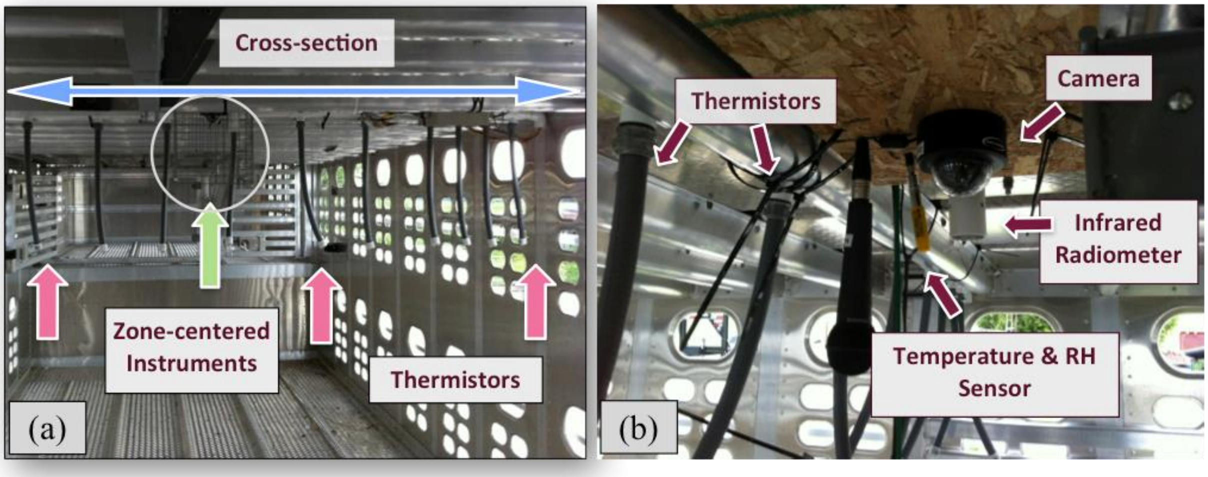

Figure 3-4. Instrumentation location overview. (a) Trailer cross-section and (b) zone-centered instrumentation board. The zone-centered instrumentation board consisted of one connection box for thermistor sensors and one zone-centered air temperature and relative humidity probe, and pig exposed surface temperature sensor.

To protect the computer from vibration during transport, a custom-fabricated enclosure was placed in the corner of the data acquisition center (Figure 3-5a). Before each monitoring trip, a wooden gate was put in front of the data acquisition center to assure secured data collection environment was secured from the pigs. Exposed instrumentation wirings were protected by PVC pipes or flexible metal conduits (Figure 3-5b), which avoid undesirable binding of the wires or wear from friction and potential damages from the pigs.

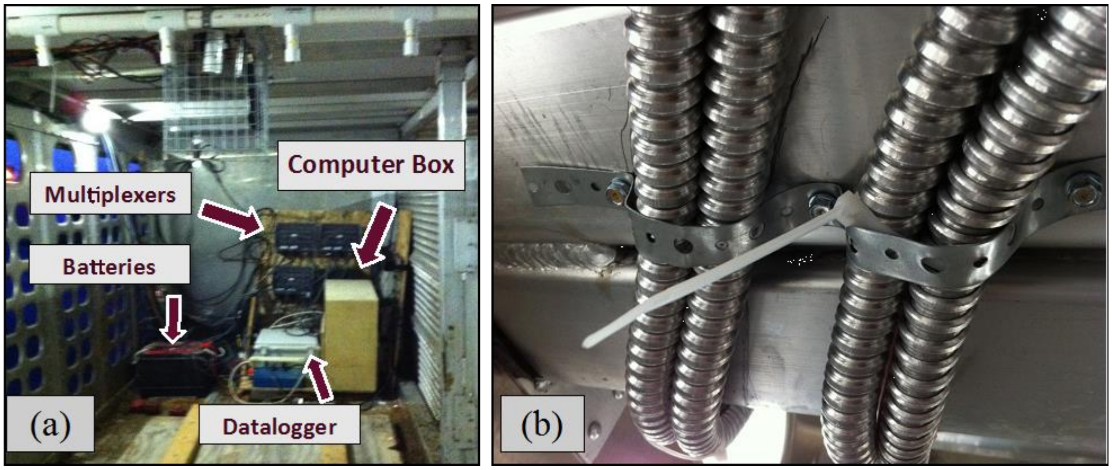

Figure 3-5. Protection for instrumentation inside the trailer. (a) The protection of data acquisition center, of which consisted of a custom-fabricated computer box with a personal computer inside, three custom-fabricated multiplexers, one datalogger, and two parallel-connected batteries, and (b) the protection of flexible metal conduits for exposed instrumentation wires within the trailer.

3.2.3 Instrumentation and Sensor Selection

3.2.3.1 *Pig Level Air Temperature*

Pig level air temperature was measured by 84 thermistors, divided into a cross-section of 14 sensors in each of the 6 zones. Each thermistor set was mounted with sensors suspended to 76 cm (30 inches) above pig height, approximately 1.2 m (48 in) above the floor, and secured to the ceiling.

A thermistor array was created using two-pin NTC thermistors (Figure 3-6, Model 10M5351, Honeywell Parts, Phoenix, AZ). The thermistor sensor has a reference resistance of 30kohm at 25°C and beta value of 4261K, with an operating temperature range from -60°C to +150°C and tolerance 0.2°C. A central voltage divider was added in each of the connection box in the 6 trailer zones to provide 5 volts power supply for the thermistors. Thermistors were soldered to a shielded twisted cable to connect from the monitoring location within the trailer to the data acquisition center, then protected from short-circuiting and damage by heat shrink and dipped in liquid tape. Due to the limitations of power input of the data logger CR23X, voltage outputs were collected for trailer internal temperature dataset.

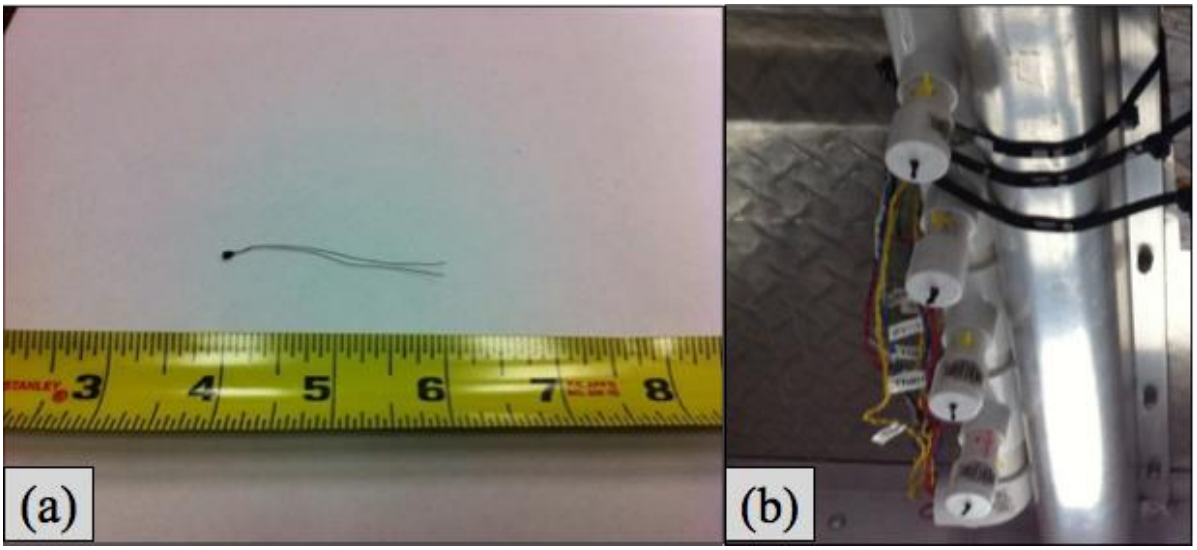

Figure 3-6. Pig level air temperature sensor (Thermistor, Model No.10M5351, Honeywell Parts). (a) 84 thermistors were implemented in 6 cross-sections within each trailer zone to measure air temperature at pigs level, and located approximately 1.2 m above pigs back. (b) Close view of the installed thermistor inside the trailer, each thermistor was protected by PVC cap and was exposed to the air to best capture the pig-level air temperatures.

3.2.3.2 *Zone-Centered Air Temperature and Humidity*

A combination temperature and relative humidity sensor [(Vaisala INTERCAP HMP60, Vaisala, Vantaa, Finland), Figure 3-7] was installed centrally at the ceiling within each zone. The zone-centered air temperature and RH sensor operates from -40°C to +60°C with a typical accuracy of ± 0.6°C and 0 to 100% relative humidity (RH) with an accuracy of ±3% to ±7% RH depending on the temperature and RH conditions.

Figure 3-7. Zone-centered air temperature and relative humidity (RH) sensor (Vaisala HMP60, Vaisala). 6 zone-centered air temperature and RH sensors were implemented at the central area at ceiling within each 6 cross-sections to measure the central air temperature and relative humidity of each trailer zone.

3.2.3.3 *Pig Skin Surface Temperature*

The integrated surface temperature within each zone of the trailer (representing pig skin surface) was measured by one infrared radiometer (Figure 3-8, Apogee SI-111, Campbell Scientific, Logan, UT) within each zone, located at the ceiling center and facing directly downward (Figure 3-4b). The infrared radiometer allows a direct measurement of exposed surface emissivity without physical contact with the surface being measured, hence derives the best indication of the exposed surface temperature. The infrared radiometer consists of a thermopile to measure exposed pigs skin surface temperature, and a thermistor to measure sensor body temperature as a reference. The Apogee SI-111 operates from -55°C to 80°C with an absolute accuracy of ±0.2°C from -10°C to 65°C and ±0.5°C from -40°C to 70°C. As commonly measured against a black body (emissivity = 1), these stated accuracy represents measurements of perfect emissivity of a flat surface, and does not represent actual field conditions where the skin, hair, and surface angles depart from a perfect emissive condition. Because of this limitation, pig-to-pig exchange during transport may cause potential variation in skin temperature that is measured. The sensor has a half angle field of view of 22° degree, which allows it to cover an approximate 0.1 m^2 area of the exposed skin surface measurement, with a measuring radius of 0.3 m.

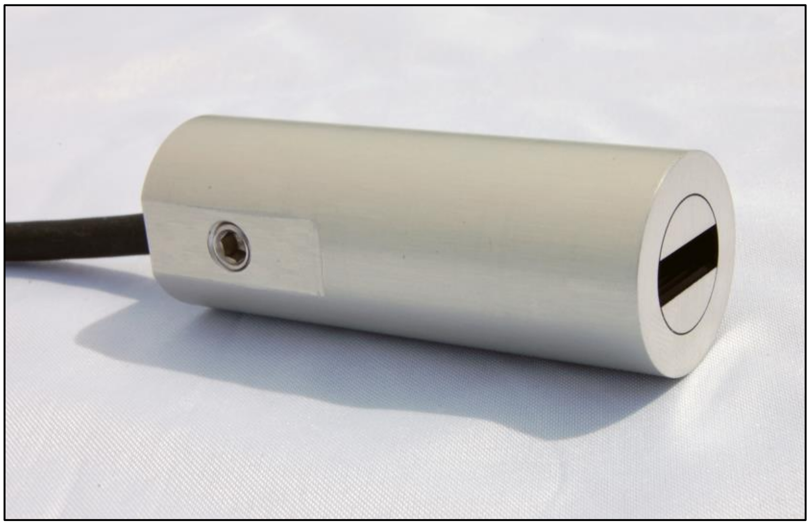

Figure 3-8. Exposed surface temperature sensor (Apogee SI-111, Campbell Scientific, Logan). 6 infrared radiometers were implemented at the central ceiling within each of the 6 cross-sections to measure the exposed pigs skin surface temperature.

3.2.3.4 *Floor and Bedding Temperature Sensors*

The bedding temperature was measured by multiple stainless steel encapsulated thermistors with built-in loggers (iButton) (DS1921G-F5, Maxim, San Jose, CA) placed on the floor within each of the 6 zones in the trailer, encased in a protective holder (Stuff-A-Ball Dog Toy, Kong Company, Golden, CO) with a measured diameter of 6.35 cm (Figure 3-9a). Three to six rubber balls with iButton sensors were randomly placed on the bedding in each zone at the start of transport to best represent the micro-climate near the floor and similar to the expected bedding temperature, which would be influenced by both the air and floor surface.

The iButton sensors are small (approximately 2.5 cm diameter) and self-contained devices with an operating range of -40°C to 85°C and accuracy of ±1°C from -30°C to +70°C and ±1.3°C outside that range.

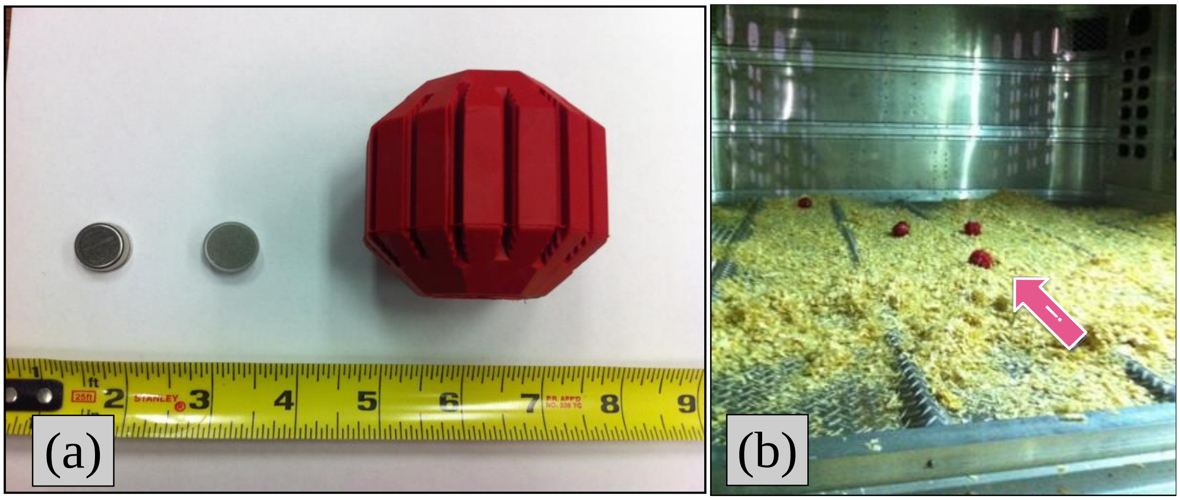

Figure 3-9. (a) Floor/Bedding Temperature Sensors (iButton DS1921G-F5, Maxim, San Jose, CA) components, and (b) Three to six ibutton sensors ibutton sensors enclosed in protective rubber balls were placed on the bedding within each of the 6 zones at the start of transport to measure the floor/bedding temperature experienced by the pigs during transport.

3.2.3.5 *External Weather Conditions*

External environmental conditions (ambient temperature and solar radiation) were collected by a HOBO stand-alone weather station kit (Figure 3-10a, U30-NRC-SYS-B, Onset Computer Corporation, Pocasset, MA) with a sampling rate of every ten minutes. The weather station consisted of a HOBO U30 NRC data logger, a 12-bit remote temperature and relative humidity sensor (S-THB-M008) and a solar radiation sensor (S-LIB-M003). The weather station kit was mounted in between the tractor and the trailer, on the front surface of the trailer (Figure 3-10b).

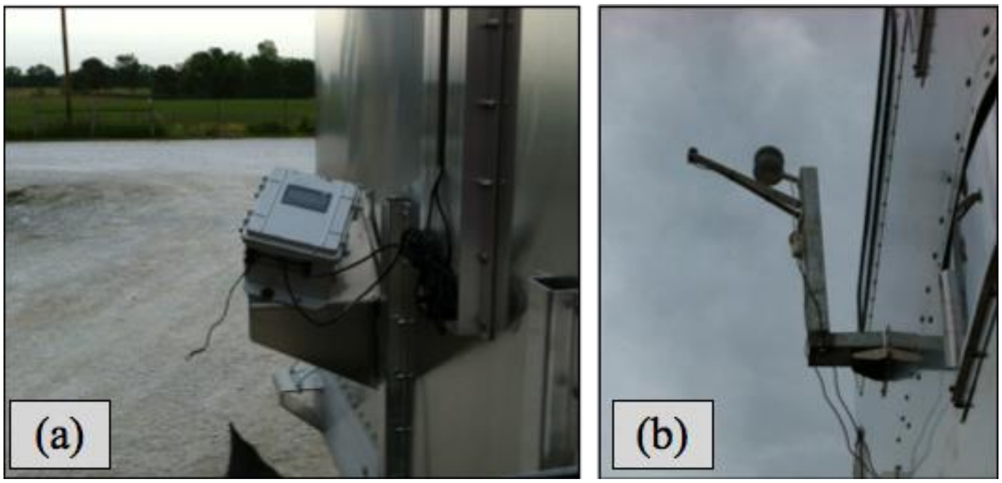

Figure 3-10. External environmental sensors. (a) A stand-alone weather station kit (U30-NRC-SYS-B, Onset Computer Corporation, Pocasset, MA) consisted of a datalogger (U30), remote temperature and relative humidity sensor (S-THB-M008) and a solar radiation sensor (S-LIB-M003) was mounted in front of the trailer to capture the external ambient weather conditions (b).

3.2.3.6 *Trailer Speed Sensor*

The trailer speed and location were monitored by a USB GPS passive tracker (iTrail, Sleuth Gear Track) at a 10-minute sampling rate. The iTrail is a passive GPS logger that records the trailer's exact location, speed, and time, and can record up to 120 hr of data. Through Google Maps and Google Earth, a map showing the trailer's location, a trailer speed report could also be generated based on the recorded data.

3.3 Sensor Calibrations

To improve confidence of data sets in data processing and analysis, the pig level air temperature sensors, zone-centered air temperature and relative humidity sensors, and the external ambient temperature and the humidity sensor were checked for performance and, if needed, calibrated under a laboratory environment, and all other sensors were assessed for the manufacturer's performance claims prior to the first deployment in the trailer and/or after the final deployment in the trailer.

3.3.1 Calibration Method

The calibration method for the thermistor temperature sensors was developed based on thermistor relation between resistance R and temperature T, as shown in Equation 3-1.

$$ln\left(\frac{R}{R_o}\right) = \beta\left(\frac{1}{T_m} - \frac{1}{T_o}\right) \qquad \text{(Equation 3-1)}$$

Where

R_0 =30,000Ω is the reference resistance at reference temperature T_0 = 273.15K + 25°C=298.15 K.

β = 4261 (ln(1/K)) is an unique characteristic representing different resistors.

T_m is the measured temperature computed by the relation between voltage output and measured thermistor resistance R.

The calibration curves were achieved by regressing T_m against reference standard temperature, using linear least squares with the following nomenclature (Davis, 2005; Green, 2003):

$$T_{act} = \frac{1}{b}\left(T_m - a\right) \qquad \text{(Equation 3-2)}$$

Where

T_{act} is the temperature measured by reference temperature devices, and is the best estimate of predicted temperature measurement (T_{pred}).

a is the intercept.

b is the slope.

For all 84 thermistor sensors, the standard error of the predicted temperature was computed to quantify the uncertainty of each sensor in future measurements, as shown in Equation 3-3.

$$S_e(T_{pred}) = \frac{S_e(T_m)}{b} \quad \text{(Equation 3-3)}$$

Where

$S_e(T_{pred})$ is the standard error of the predicted temperature.

$S_e(T_m)$ is the standard error of the measured temperature.

b is the slope.

3.3.2 Pig Level Air Temperature Sensor Calibration

All 84 thermistor sensors were calibrated over the range from -15°C to 45°C using an environmental controlled chamber against a NIST certified temperature device (Rotronic NT213) for the range 10°C to 45°C and a temperature controlled recirculating water bath (Neslab RTE-211, Artisan Scientific Corporation, Champaign, IL) for the range -15°C to 10°C.

Based on data derived from thermistor test, an example of the accuracy of thermistors is summarized in Chapter 4. Accuracy analysis is based on the Se (T_{pred}) values in this study.

3.3.3 External Environment Sensor Calibration

The external air temperature and relative humidity sensor was calibrated over the range from -15°C to 40°C using the same calibration method, against an NIST certified block temperature calibrator (CL-134, OMEGA, Stamford, CT).

3.4 Trailer Pre-monitoring Setup Procedure

According to TQA guidelines [as described in 1.5.6 (Table 1-1)], trailer management strategies may be implemented to adjust the thermal environment inside the transport trailer. In cold weather conditions, boarding of trailer openings (Figure 3-11a) and variation in amount of bedding (Figure 3-11b) may limit cold air entering the trailer and provide insulation for the pigs.

In addition to the TQA guidelines for trailer boarding and bedding setup procedures, misting cooling inside the trailer and/or with fan operation external to the trailer during hot weather is recommended when available. Accordingly, we developed a set of procedures following these guidelines to employ during some warm and hot weather trips (Table 3-2).

Table 3-2 Truck setup procedures developed for specified outside temperatures in hot, mild and cold weather

Temperature °C (°F)	Protocol Arrangement			Combination
	Boarding	Bedding	Misting	
< -12 (10)	90%with bottom boarding covered	Heavy	None	1
-12 ~ -6 (10-19)	75%	Heavy	None	1
-7~3 (20-39)	50%	Medium	None	1
4~9 (40-49)	25%	Medium	None	1
10~20 (50-69)	0	Medium	2 methods or none	3
21~26 (70-79)	0	Medium	2 methods or none	3
27~31(80-89)	0	Light	2 methods or none	3
>32 (90)	0	Light	2 methods	2

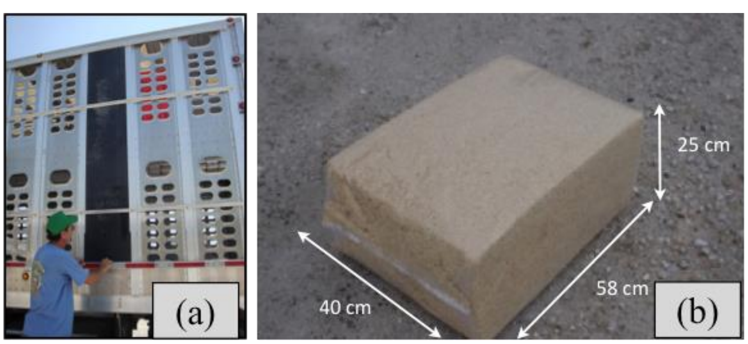

Figure 3-11. Trailer management strategies for thermal environment inside the trailer during cool and cold conditions. (a) Boarding of the trailer by covering openings and (b) Substrate material (1 bag) that was scattered over the trailer floor prior to each monitoring trip.

3.4.1 TQA and Alternative Boarding Arrangement

Boarding indicates a covering of the trailer openings, which may include plugs or side slats that are put outside of the trailer surface to reduce the amount of cold air entering the trailer. The trailer in this study incorporated side-slats (Figure 3-11a). The boarding coverage recommendations vary from 0-90% and are based on outside temperatures (Table 1-1 and Table 3-2).

According to Table 3-2, 90% boarding with bottom edge covered arrangement (Figure 3-12a) was implemented when ambient temperature was below -12˚C (10˚F). 75% evenly distributed boarding percentage (Figure 3-12b) was conducted when outside temperature ranged between -12 and -7°C (10 to 19°F). 50% evenly distributed boarding percentage (Figure 3-12c) was implemented when outside temperature ranged from -7 to 4°C (20 to 39°F). 25% evenly distributed boarding percentage (Figure 3-12d) was implemented when outside temperature ranged between 4 and 9°C (40-49°F). For outside temperature that was above 4°C (39°F), the trailer should be completely open.

Due to different outdoor temperature conditions and the varying combination completion, three alternative boarding arrangements were applied to explore the effects of different boarding placements on the air distribution within the trailer (Figure 3-13). For temperature range -7-4°C (20-39°F), trips with 50% boarding more towards rear (Figure 3-13a) and trips with 50% boarding all at rear (Figure 3-13b) were completed; for temperature range 4-9°C (40-49°F), trips with 50% boarding evenly distributed and trips with 25% boarding more towards rear (Figure 3-13c) were implemented. All of the alternative arrangements were employed with heavy bedding arrangement.

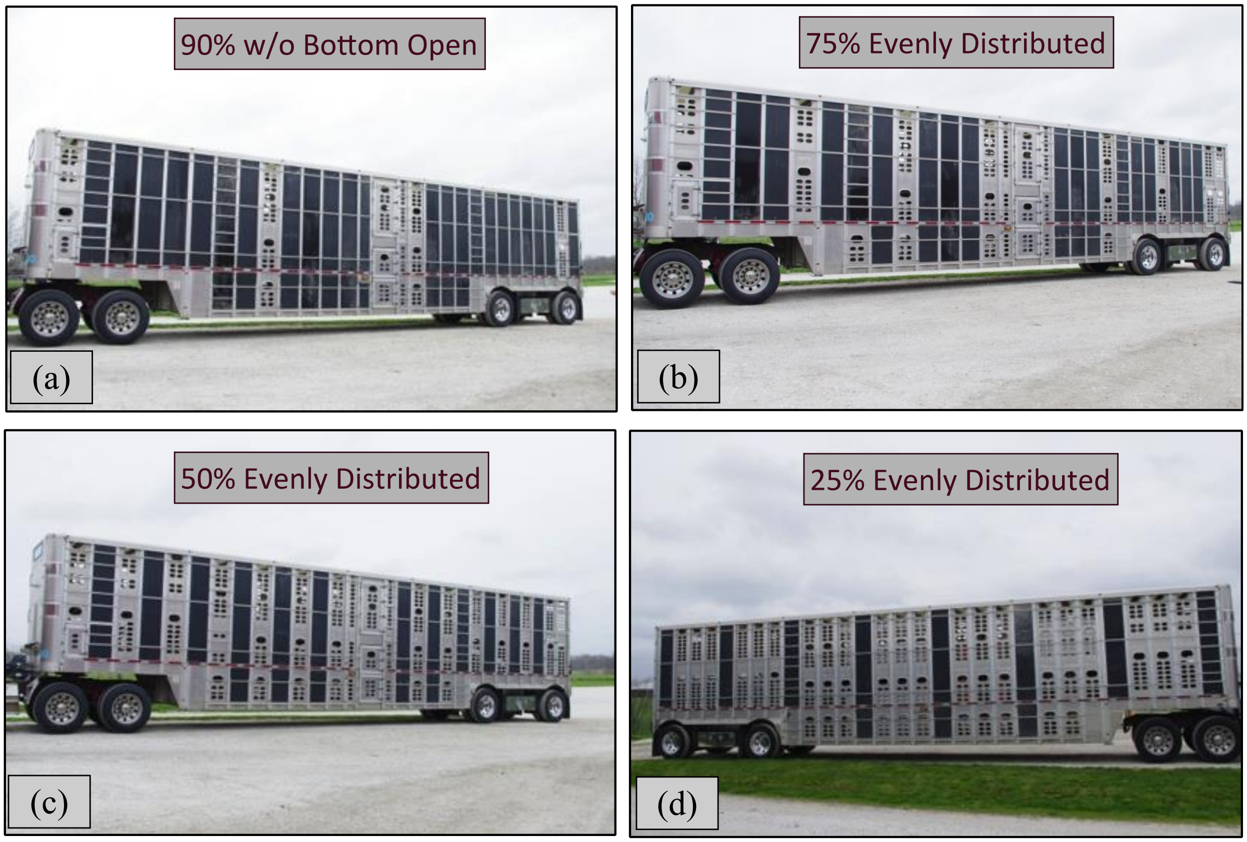

Figure 3-12. TQA typical boarding percentage arrangements assessed for cold weather conditions. (a) 90% boarding with bottom covered, (b) 75% boarding coverage evenly distributed, (c) 50% boarding coverage evenly distributed, and (d) 25% boarding coverage evenly distributed.

Figure 3-13. Alternative boarding placement arrangements assessed in cooperation with outside temperature and monitoring completion, for temperature -7 to 9°C (20 to 49°F). (a) 50% boarding more towards rear, (b) 50% boarding all at rear, and (c) 25% boarding more towards rear. Left indicates the front of the trailer and right indicates the back of the trailer.

3.4.2 TQA Bedding Arrangement

Bedding indicates the placement of a substrate material, commonly wood shavings, onto the trailer floor prior to loading pigs onto the trailer. The bedding provides the pigs with some traction to reduce instances of slipping or falling while walking through the trailer, absorbs liquid, and may also have some thermal benefit in cool or cold weather. The amount of bedding was characterized by the number of bags and total volume of the bedding materials applied. For this study, each bag had a dimension of 25 cm (10.5 in) × 58 cm (23 in) × 40 cm (16 in) and a total volume of 0.06 m^3 (2.2 ft^3) (Figure 3-11b). The total bedding amount applied inside the trailer was designated as follows: light bedding indicated 1 or 2 bags [0.06 to 0.12 m^3 (2.2 to 4.4 ft^3)] of bedding, medium bedding indicated 3 bags of bedding [0.18 m^3 (6.6 ft^3)], and heavy bedding indicated 4 bags or 6 bags of bedding [0.24 to 0.36 m^3 (8.8 to 13.2 ft^3)].

According to Table 1-1 and Table 3-2, heavy bedding was applied when outside temperature ranged below -12°C (10°F), medium bedding was employed for outside temperature ranged between -12 and 4°C (10 to 39°F) and light bedding was used for outside temperature that was above 4°C (39°F).

3.4.3 Field Practices of Misting

Misting is a cooling strategy applied in pork industry, both in barns and in the transport setting. In this observational study, misting indicates spraying water on pigs back or on the bedding materials within the trailer when the trailer is stationary at swine barns or the abattoir when available. Twenty misting nozzles [Figure 3-14a, TX-V626, Teejet Technologies (2 in Zone 1, 6 in Zone 2, 2 in Zone 3, 1 in Zone 4, 6 in Zone 5, and 3 in Zone 6)] were included within the trailer used in this study; the cooling effects of the misting were observed and evaluated during the study. The misting nozzles on the bottom level were located along the middle length of the trailer, and those on the top level were located along the right side length of the trailer. The misting nozzle had a maximum operating pressure of 300 psi (20 bar) and a spray angle of 80° at 100 psi (7 bar).

In this study, two industry practices of misting methods, including misting during loading and misting after loading were evaluated in warm to hot weather conditions. Based on different outdoor temperatures, and availability of cooling facilities, three misting methods were assessed before transport for temperature 26°C (80°F) and above. For monitoring trips that were within 26 to 32°C (80-90°F) outdoor temperature range, misting during loading, misting after loading, and no misting during loading were observed and documented. When the ambient temperature exceeded 32°C (90°F), misting, either during loading or misting after loading, was always done. Additionally, misting inside the trailer and/or with fans external to the fans (Figure 3-14b) was applied while waiting to unload pigs at the abattoir, when available.

According to our observation, in general, the duration of misting after loading method lasted for 10 minutes, the duration of misting during loading depended on loading period, and the duration of misting inside the trailer and/or with fan operation external to the trailer depended on the accessibilities to misting facilities when the trailer stopped at the abattoir.

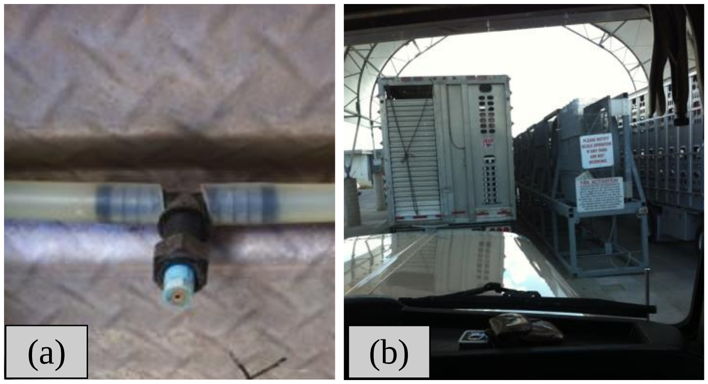

Figure 3-14. Trailer management strategies for thermal environment of the trailer during warm and hot conditions. (a) Misting nozzles (TX-V626, Teejet Technologies) that were implemented inside the trailer, and (b) trailer location with respect to the fan bank when waiting to unload pigs at the plant.

3.5 Monitoring Documentation and Data Categorization

In this study, each monitoring trip was summarized by time periods correlating to the presence of pigs on the trailer as well as just after unloading (Figure 3-15). Time periods were defined as: *before loading*, *before transport* (loading, misting, waiting at the barn), *during transport* (between the barn and the destination), *after transport* (waiting prior to unloading, with and without misting and/or with fans, unloading), and *after unloading*. The monitoring trip was considered final when the last pig was unloaded from the trailer. Trailer interior condition with instrumentation deployed and pigs on the trailer for each critical time period is shown in Figures 3-15a and 3-15c. Prior to each monitoring trip, loading schedules were cooperated with the trucking company (Mt.Sterling, IL), the pork processing plant (Beardstown, IL or Monmouth, IL) and collaborating swine producers (various locations around western IL, eastern IA, and northern MO). For each monitoring period, the trailer usually departed from the trucking company home location and loaded pigs at different swine farm locations. The durations for transport had a wide distribution because the location of swine farms differed geographically.

Figure 3-15. Trailer interior conditions with instrumentation deployed and pigs on the trailer for (a) while loading, (b) after loading, before transport period, and (c) after unloading.

During each monitoring trip, local weather was monitored and documented for each time period. Upon arrival at the abattoir, dead or down (DOD) pigs upon arrival were documented for each monitoring trip. The outdoor temperature and relative humidity data are also derived from national weather station database and corresponding transport location data derived from GPS sensor. A summary table of completed trips according to TQA management procedures was developed in which temperature data were categorized with trailer management combinations in specified ambient temperature range. The following categorization scheme was employed: trips monitored when ambient temperature exceeded 10°C were classified as hot trips, while trips monitored when ambient temperature was below 10°C were classified as cold trips. According to Table 3-2, ambient temperature recorded in the middle of the transport period was used for all monitored trips to categorize the correlative outside temperature range of each monitoring trip. Ambient temperature recorded at the start of the loading period was used to determine misting and boarding arrangements for hot trips and cold trips, respectively.

Varied by boarding arrangements, trips monitored with boarding implementations in this study are as well categorized as TQA typical or alternative trips. The TQA typical boarding arrangement refers to an evenly boarding distribution outside the trailer surface, which is the most widely applied boarding implementation among truck drivers. During monitoring, TQA typical boarding arrangement was first employed to complete specific ambient temperature categories. In addition to the completion of TQA typical trips, alternative trips with variation in boarding distribution and rate were explored for applicable ambient temperatures to assess the effects of boarding placement on the air distribution within the trailer.

3.6 Data Processing

3.6.1 Preliminary Data Processing

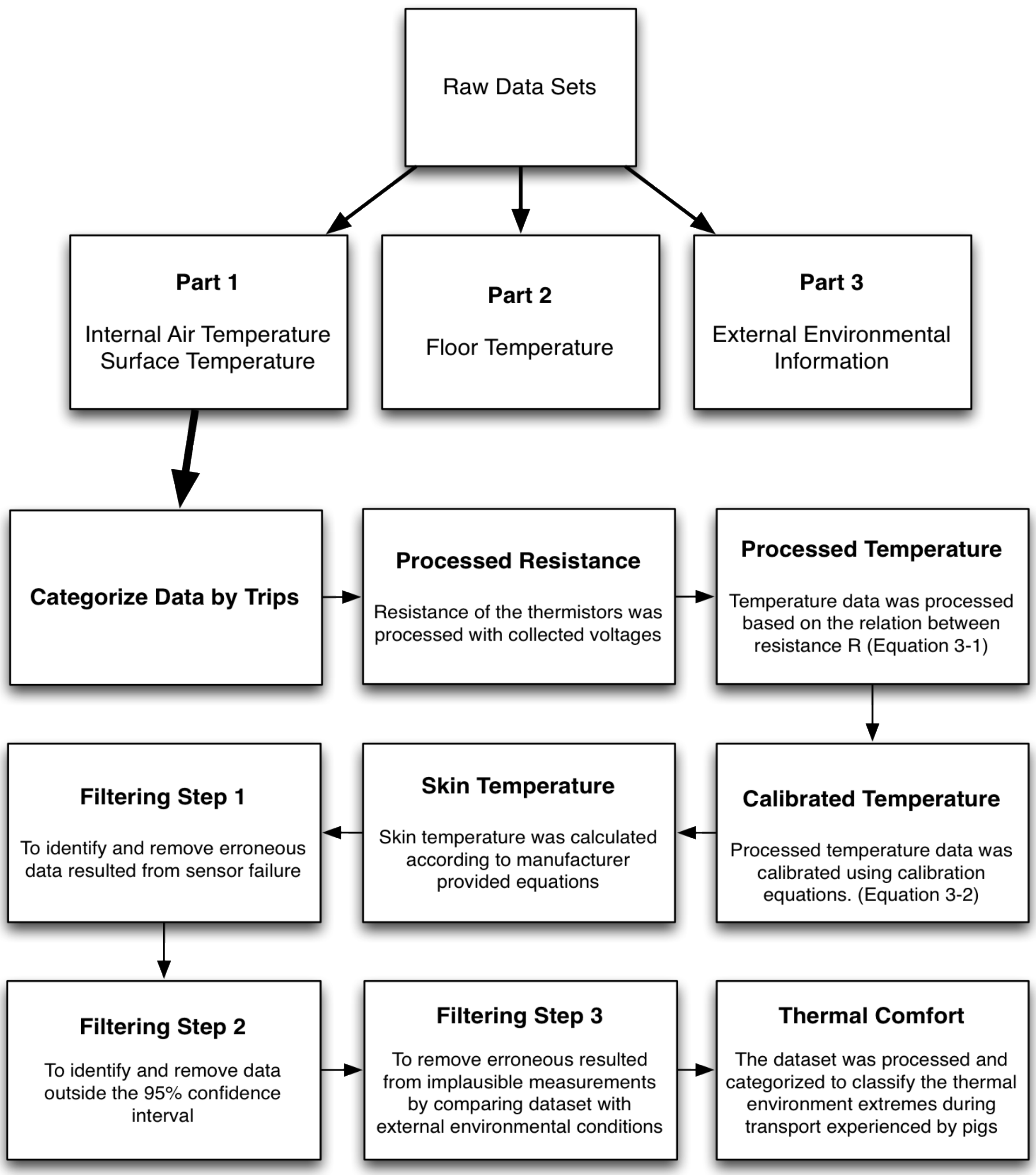

Figure 3-16. Raw data set components, preliminary data processing schematics, filtering methods, and overall schematic for thermal environment categorization for pig air temperature and skin surface temperature.

As shown in Figure 3-16, the raw data set consisted of three parts: Part 1) air temperature near pig level (measured by thermistor temperature sensors), zone-centered air temperature and relative humidity (measured by Vaisala Intercap Probes), and integrated pig skin surface temperature (measured by infrared radiometers); Part 2) floor temperature (measured by iButton temperature sensors); and part 3) external environmental information, including ambient temperature and solar radiation (measured by HOBO U30 weather station). Raw data Part 1 – downloaded from the Campbell Datalogger CR23X after each monitoring day (typically 1 to 3 trips). Raw data Part 2 and Part 3 were downloaded after every full monitoring period (typically 5 to 7 trips).

The raw data set was manually separated by timing of each period during each trip; separated data file was processed and filtered using macros in Microsoft Excel. Tools were created in Macro/VBA to process the repetitive calculations for every data file, and were organized into three main steps. The original data format was kept while data processing process was achieved more efficiently and systematically. During data processing, the voltage outputs were first converted to resistances by manufacturer provided equations. After the temperatures were processed, the calibration curves for each thermistor sensor were applied to the processed temperature. The skin temperature data set was processed using equations provided by the manufacturer. For

3.6.2 Data Filtering

The goal of the filtering was to remove erroneous data without compromising environmental measures. On several occasions, erroneous data were observed in the data set, in some cases likely the result of frost, unexpected moisture, or extreme cold conditions. Air temperature collected by the thermistors was filtered using a three-step process.

3.6.2.1 *Filtering Step 1-Identifying Sensor Failure*

The first filtering step was developed to identify and remove erroneous data resulted from sensor failure. In this step, the calibrated temperatures were assessed with a logical method by comparing with zone-centered air temperature ± 35°C. Temperature measurements that were outside this range were removed. Zone-centered air temperature was selected as a comparison parameter for the first filter because of the stable performance of the Vaisala temperature/RH probes and the proximity to the thermistors. The ± 35°C was selected as the acceptable range based on a manually assessed signal output when sensor connection failures were observed.

3.6.2.2 *Filtering Step 2-Identifying Data Outliers*

A second filtering step was developed to identify and remove remaining data outliers. By taking the average, median, and standard deviation of the temperature data processed by filtering step 1, a 99.7% confidence interval that includes 99.7% of the population was built. By applying filtering step 2, any data that are outside the range of 99.7% confidence interval [average temperature ± 3SD (standard deviation)] was removed. This statistical method has been widely adopted for identifying outliers (Johnson et al., 2011; Ott and Longnecker, 2010).

3.6.2.3 *Filtering Step 3-Identifying Implausible Measurements*

In the third filtering step, external ambient temperature information recorded from local weather stations during each monitoring trip was compared with the remaining air temperature data. After a manual assessment of the dataset with thermal environmental information, there is sufficient evidence to believe that the thermal temperatures inside the trailer should be higher or no less than 10°C lower than the outside temperatures. Thus, any data points that were lower than outside temperature minus 10°C were removed from dataset.

3.7 Data Analysis

3.7.1 Overall Characteristics of Thermal Environmental Data

3.7.1.1 *Duration of Transport Phases with Pigs on the Trailer*

Of all monitoring trips, the time of important events was recorded, and a box and whisker plot was computed to represent the distribution of the overall transport duration with pigs on the trailer for three events: *before transport* (loading, misting, waiting at the barn), *during transport* (between the barn and the destination), and *after transport* (waiting prior to unloading, with and without misting and/or with fans, unloading). A horizontal box-and-whisker plot was created to represent the distribution. In the box-and-whisker plot for overall transport duration, an X indicates the average value of the duration of transport for each event, and the box and whiskers indicate the 0, 25, 50, 75, and 100 percent quartiles, where each percentile indicates to the upper end of the corresponding percentage of the measurements below or equal to it (Johnson et al., 2011; Ott and Longnecker, 2010). Within the box-and-whisker plots, the x-axis indicates the distribution of temperature or duration measurements, and the y-axis indicates corresponding event periods within which the measurement occurred.

3.7.1.2 *Overall Thermal Conditions*

The internal air temperature data set was processed and categorized to classify the thermal environment during transport and duration of exposure. Pig-level air temperature was processed to represent the occurrences of interior trailer temperatures. Previous studies have provided referential information of critical temperatures involved in pig's thermoregulatory processes, such as thermoneutral zone, lower critical temperature and upper critical temperature (NRC, 1981; Brown-Brandl, 2012; Baker, 2004). In this study, thermal comfort conditions are further categorized into seven specific trailer internal temperature ranges: extreme cold (T_{in} < -15°C), cold (-15°C < T_{in} < 0°C), cool (0°C < T_{in} < 18°C), thermoneutral (18°C < T_{in} < 25°C), warm (25°C < T_{in} < 30°C), hot (30°C < T_{in} < 35°C), and extreme hot (T_{in} > 35°C).

The Temperature-Humidity Index (THI) was processed with the following nomenclature $THI = 0.8T_{db} + RH(T_{db} - 14.4) + 46.4$ (Equation 1-3), using the zone-centered air temperature and relative humidity to calculate THI and classify the occurrences of livestock weather and safety index conditions [LWSI, (LCI 1970)]. The Livestock Weather Safety Index conditions associated with THI values are categorized into four ranges: Normal (THI ≤ 74), Alert (75 ≤ THI ≤ 78), Danger (79 ≤ THI ≤ 83) and Emergency (THI ≥ 84) (NRC, 1981; LCI, 1970; Hahn et al., 2009).

If an interior temperature or LWSI condition occurred at any time and at any location during the monitoring while pigs were on the trailer, then this occurrence was counted. A summary frequency table was developed, in which the occurrence of these conditions was tabulated for each of the temperature or LWSI ranges. Each cell within the table corresponding to a given temperature or LWSI range for each ambient condition was colored, and the upper number inside each colored cell indicates the number of trips in which this condition was recorded. A single trip may experience multiple ranges of thermal comfort, and all the thermal comfort conditions encountered were counted for each trip. The frequency of occurrence for each thermal condition and livestock weather and safety condition was represented by the percentage of the total occurrences for that monitoring trip. The bottom number in each colored cell represents the range of trip observations for that condition. For example, a range of 0-10% would indicate that at least one trip had no observations in that category and at least one had 10% of the observations in that category. For LWSI analysis, the frequency of occurrences was only processed for monitoring trips that encountered danger and emergency LWSI conditions. The pigs were considered to be exposed to thermal extremes if they experienced either extreme cold-temperatures or extreme hot-temperatures, or emergency safety condition during a trip.

3.7.1.3 *Temperature Distribution inside the Trailer*

Temperature distribution patterns were developed to demonstrate the distribution of temperatures, and by inference, the ventilation patterns within the trailer. Cooler regions indicate proximity to an air inlet and hotter regions indicate air outlets when located next to a wall because the air would have been warmed as it passed over the pigs. The pig-level temperature data set was linearly interpolated in Matlab® at every minute to construct a series of animations to visualize the effects of the different trailer management on the thermal conditions within the trailer for both top level and bottom level over the monitored broad ambient temperature range. Due to the complexity of extrapolation from the sensors to the outside boundary of the trailer, only areas within which the front temperature sensor set to the rear sensor set were installed on both levels were included in the animations, excluding the area inside the trailer between the front wall and the front sensors and the area between the rear wall and the rear sensors. In the animation, a color bar was created to indicate the animated air temperature, of which red indicates hotter temperatures and blue indicates cooler temperatures. Extreme temperatures were chopped from the color bar to better represent the thermal distribution patterns. The pig-level air temperature sensors are also shown as green circles in the animations to visualize the sensor locations within the trailer, failed sensors due to environmental conditions were excluded from the animation (occasionally leaving a non-colored area in the animation), and the trailer dimension was marked in the animation to indicate corresponding locations, where the x-axis indicates the trailer length and the y-axis indicates trailer cross section. The animations were created at a speed of 5 frames per second, and a colored text box will appear on the animation to notify events occurred in the monitoring trip.

3.7.1.4 *Zone-specific Skin Temperature and THI Distribution*

To specify the problematic areas within the trailer for *during transport period*, several bar charts were generated to represent the following analyses: zone-specific skin temperature distribution, and zone-specific THI distribution.

Trailer internal temperature dataset were included in these analyses, and were further specified into extreme cold-temperature trips, cold-temperature trips, hot-temperature trips, and extreme hot-temperature trips to best represent the occurrences of interior trailer skin temperature and THI extremes for moderate and worst-case scenarios. In these analyses, trailer interior locations were categorized as followed: Zone 1 and Zone 4 represent the top and bottom compartments in the front sections of the trailer, Zone 2 and Zone 5 represent the top and bottom compartments in the middle sections of the trailer, and Zone 3 and Zone 6 represent the top and bottom compartments in the rear sections of the trailer. For each monitoring trip, the maximum and the minimum skin temperatures during *transport period* were processed, and the corresponding locations within which these occasions occurred were documented. For each zone within the trailer, the analysis schematics were generated as followed: the occurrences of the maximum and the minimum skin temperatures and the maximum THI were counted, the total numbers of the monitoring trips evaluated were counted, the frequency of the occurrence of corresponding locations was computed for the skin temperature and THI measurements described in 1) and was shown as percentage values.

3.7.1.5 *Overall Floor Temperature Distribution*

Floor temperature data set for all monitoring trips was included to assess the floor temperature range for all events before loading, before transport, during transport, after transport, and after unloaded during hot, mild, and cold weather conditions. For each event period in each monitoring trip, minimum, mean and maximum floor temperatures of the entire trailer were used to create a box-and-whisker plot to graphically represent the distribution of floor temperature for time periods.

3.7.1.6 *Effects of Bedding Depth on Pig Skin Temperature Measurements*

The floor temperature data set for all completed monitoring trips was categorized to classify the overall floor/bedding thermal conditions experienced by pigs during the transport period. Zone-centered air temperature data was associated with floor temperature data to evaluate the effects of three bedding depths on pig skin temperature. The three bedding depths evaluated were: light bedding, medium bedding, and heavy bedding as described in 3.4.2. Two measurements were performed as followed: zone-centered air temperature data was averaged for all 6 zones within the trailer to represent trailer interior air temperature for each monitoring trip, and the associated bedding depth was documented, and floor temperature data was averaged for all floor/bedding sensors to represent the overall floor/bedding temperature of the trailer, and the associated bedding depth was documented. Zone-centered air temperature was plotted against pig skin temperature to explore any deviations in relationship due to different bedding depths.

3.7.1.7 *Effects of Boarding Percentage on Pig Skin Temperature*

The trailer internal zone-centered air temperatures and pig skin temperatures was processed and categorized for all completed monitoring trips to evaluate the effects of boarding percentage (vary from 0% to 90% as described in 3.4.1) on pig skin temperature. The relationship between pig skin temperature, variable trailer boarding percentage arrangement, and corresponding zone-centered air temperature was plotted in a scatterplot.

Of all the trips evaluated, the following analyses were completed: the minimum pig skin temperature that was observed *during transport period*; the maximum pig skin temperature that was observed *during transport period*; the average pig skin temperature *during transport period* for each monitoring trip evaluated; the corresponding boarding percentage for each monitoring trip associated with the minimum skin temperature; and the corresponding zone-centered air temperature during transport in the same zone that the minimum skin temperature and the maximum skin temperature were recorded.

For each trailer boarding percentage, the minimum skin temperature, the maximum skin temperature, and the average skin temperature were plotted against the corresponding zone-centered air temperature. The relations between the minimum and the maximum pig skin temperature and the corresponding boarding percentage were explored in scatterplots to illustrate the effectiveness of different boarding percentage on pig skin temperature measurement. The relation between the average pig skin temperature and the corresponding boarding percentage was shown as a reference.

3.7.1.8 *Effects of Short Breaks during Transport on Trailer Thermal Environment*

During transport period with pigs on the trailer, trailer operator may stop intermittently for short breaks, of which the duration may range from a few minutes to approximately an hour. To explore the potential effects of such short breaks on trailer thermal environment, a scatterplot was generated for one monitoring trip chosen under mild weather conditions (outside temperature ranged from 10 to 20°C), based on observations of qualified monitoring trips. Trailer zone-centered air temperature in each of the six zones within the trailer and the outside temperature were plotted against the elapsed time during the short breaks. The top and the bottom levels of the trailer were represented by two different line styles (dash lines to represent top level zones, and straight lines to represent bottom level zones) in the plots.

3.7.2 Assessment of Current TQA Guidelines for Hot Weather Conditions

The effects of current industry practices for hot weather conditions were assessed by the following analyses: zone-specified skin temperature distribution for hot weather conditions, zone-specified THI distribution inside the trailer for hot weather conditions, and the effects of cooling methods applied in a stationary trailer during loading period at the swine barn and prior to unloading period at the abattoir.

For zone-specified skin temperature distribution and THI distribution analyses, the same methodologies applied for overall zone-specific skin temperature distribution (section 3.7.1.4) for all monitoring trips evaluated were adapted.

For the cooling effects at the abattoir analysis, to evaluate the effects of misting before transport for cooling between the two methods of misting after loading and misting during loading, animations created in 3.7.1.3 were evaluated for effects of cooling based on the location and intensity of the colors representing the cooler temperatures, skin temperature reduction was calculated based on the start of cooling and the coolest temperature observed, the duration of the cooling was assessed by calculating the amount of time until the coolest temperature and the amount of time to warm back up to the starting temperature. The schematic for these analyses is demonstrated in Figure 3-17, and is described as followed: 1) the average wet skin temperature just prior to departure (when misting during loading or misting after loaded was completed) for all 6 zones and the time was recorded, 2) the minimum skin temperature during transport and the time at which it occurred, 3) the skin temperature during transport corresponding to the initial skin temperature was recorded in the same zone where the minimum skin temperature during transport was occurred, and the corresponding time was recorded, 4) the maximum skin temperature during transport in the same zone that the minimum skin temperature was recorded, and the time at which it occurred.

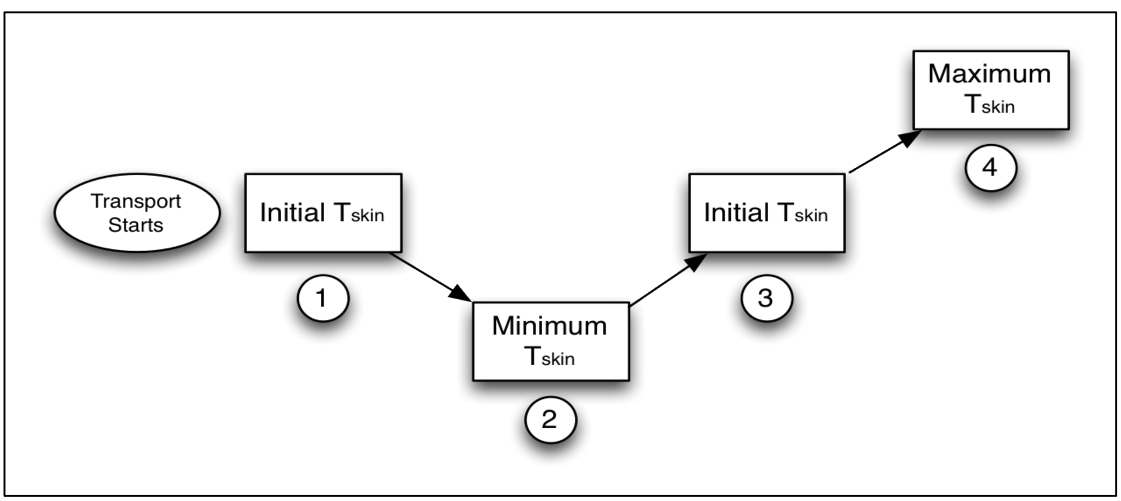

Figure 3-17. Events to determine the effects of misting before transport for cooling practices. At each event, the skin temperature, and the time at which the skin temperature occurred were recorded.

To evaluate the cooling effects of misting, four analyses were performed to explore the best-case, average, and worst-case scenarios by three approaches: the minimum zone-centered air temperature and pig skin temperature observed for all 6 zones, the average zone-centered air temperature and pig skin temperature observed for all 6 zones, the maximum zone-centered air temperature and pig skin temperature observed for all 6 zones, and the minimum, average, and maximum THI observed within the trailer for the evaluated period. The three management approaches observed were: fan operation external to the stationary trailer, misting inside the trailer with fan operation external to the stationary trailer, and no misting or fan. A Fisher's LSD mean separation test (Ott and Longnecker, 2010)] was conducted to compare the temperature and THI responses for each of the three approaches. Differences were considered significant for $\alpha=0.05$. Supplemental information, including outside temperature, transport duration, and the number of trips evaluated were also documented and performed for these three approaches.

In addition to the analyses described above, for each instance of a strategy applied, trailer zone-centered air temperature in each of the six zones within the trailer and the outside temperature were plotted against the elapsed time during the waiting period prior to unload the pigs when the trailer was stopped at the abattoir. The top and the bottom levels of the trailer were represented by two different line styles in the plots. To supplement the above analyses, monitoring trip information, DOD (dead or down pigs upon arrival) rate, temperature drop for all six zones inside the trailer, and wet-bulb temperature depression during corresponding waiting period for each of the distinguish observation were documented.

3.7.3 Assessment of Current TQA Guidelines for Cold Weather Conditions

The effects of current industry practices for cold weather conditions were assessed by the following analyses: zone-specific skin temperature distribution for cold weather conditions and the effects of heavy bedding on thermal environment inside the trailer.

For the zone-specific skin temperature distribution for cold weather conditions analysis, the same methodologies applied for overall zone-specific skin temperature distribution (section 3.7.1.4) for all monitoring trips evaluated were adapted.

To evaluate the effects of heavy bedding on thermal environment inside the trailer, three box-and-whisker plot were generated by computing correlating statistical data (including minimum, 25% percentile, median, 75% percentile, maximum, and average values) to illustrate: the distribution of the duration of which subzero floor temperatures occurred with heavy bedding in the trailer under cold conditions, the worst-case scenario distribution of the longest duration of the subzero floor conditions that were experienced by the pigs, and the distribution of time for the floor sensors to reach subfreezing conditions on an empty trailer between loads of pigs.

To achieve the three analyses described above, the original floor temperature data was categorized for all floor sensors within the trailer over the evaluated monitoring trips to create the first box-and-whisker plot. The minimum floor temperature data for all sensors within the trailer was used to perform the second box-and-whisker plot. A subset of the original floor temperature data, which included only trips with subfreezing condition prior to loading period, was used to compute the third box-and-whisker plot.

By taking average of the averaged, minimum, and maximum floor temperatures (data from the third plot), the average time for trailer to reach freezing conditions, the time at which trailer started to freeze, and the time at with the entire trailer floor reached freezing conditions were calculated.

3.7.4 Assessment of Alternative Boarding Practices for Cold Weather Conditions

To assess the effects of alternative practices for cold weather conditions, the following analyses were completed: the effects of trailer boarding variations on the distribution of trailer interior air temperature and pig skin temperature, the effects of boarding percentage on zone-centered air temperature and pig skin temperature, and the effects of boarding distribution on zone-specific skin temperature distribution. All monitoring trips evaluated were conducted under the same outside temperature range.

To evaluate the effects of TQA typical and alternative boarding variations on pig skin temperature measurements, the same analyzing principle performed in 3.7.1.7 was applied when this analysis was further carried out by monitoring trips assigned with TQA typical boarding percentages and monitoring trips designated with alternative boarding placement arrangements. For both the monitoring trips with TQA typical boarding percentage and the monitoring trips with the alternative boarding arrangements, the minimum, average, and maximum pig skin temperature was plotted against the corresponding zone-specific air temperature in a scatterplot. The minimum, average, and maximum pig skin temperatures were demonstrated by different shaped symbols, while TQA typical boarding percentages and the alternative boarding arrangements were shown by different colors.

Trailer internal zone-centered air temperatures and pig skin temperatures were included and analyzed for the effects of variable trailer boarding placements with identical trailer boarding percentage and the effects of variable trailer boarding percentages with identical trailer boarding placements. To achieve the analyses described above, the minimum zone-centered air temperature, the maximum zone-centered air temperature, the minimum pig skin temperature, and the maximum pig skin temperature were observed during *transport period* with pigs for all locations within the trailer.

For the effects of varying trailer boarding distribution on thermal environments, all four observations described in the previous paragraph were completed for three different trailer boarding distributions assigned with the same trailer boarding percentage. These three trailer boarding distributions were: 50% trailer boarding percentages with boarding panels evenly distributed outside of the trailer, 50% trailer boarding percentages with more boarding panels distributed towards the rear of the trailer, and 50% trailer boarding percentages with all boarding panels distributed at the back of the trailer. These analyses were conducted within the same outside temperature range.

For the effects of varying trailer boarding percentages on thermal environment analysis, the same four temperature measurements were explored for two different trailer boarding percentages that were conducted with the same distribution, including 25% boarding panels evenly distributed and 50% boarding panels evenly distributed. Observations for both were made with the same outside temperature range.

For both analyses described above, a Fisher's LSD mean separation test (Ott and Longnecker, 2010) was conducted to any differences between the mean of varying boarding practices for each of the temperature measurement mentioned above. The effects of any boarding practice was considered significant for α=0.05.

3.8 Limitation and Challenges

Due to the difficult nature of the research, the biggest challenge was attaining data for the entire TQA arrangement protocol table based on in order to represent all weather conditions across the range of outdoor conditions. The monitoring trips were usually scheduled with the cooperating trucking company two weeks before execution. For extreme weather conditions, especially the coldest conditions, flexible schedules were conducted to best fit the weather conditions to TQA arrangement protocol table, but timing of trips was still challenging.

Power supply shortages occurred during several consecutive trips, mainly due to the large power requirements from the computer, monitor and inverter. To compensate for this challenge, the computer and monitor were adjusted to power-saving mode during transport trips. A portable battery charger was also used to charge the batteries continually to extend the usage span of the batteries when applicable.

Sensor losses occurred periodically throughout the study, especially in cold conditions, likely due to unavoidable damage resulting from trailer vibration, contacts from the pigs, extreme weather exposure, etc. These limited challenges were solved by replacing or re-wiring the sensors as needed before each monitoring trip, and were implemented as needed through the entire monitoring period.

CHAPTER 4. RESULTS AND DISCUSSION

4.1 Sensor Calibration

4.1.1 Pig Level Air Temperature Sensor Calibration

Based on data derived from thermistor calibration (Appendix A), the accuracy of the pig level air temperature sensors is summarized in Table 4-1. Within the table, CH 1-1 to CH 6-14 identifies the corresponding thermistors in the corresponding cross-section zone 1-6 within the trailer, etc., and Se (T_{pred}) represents the standard error of the predicted temperature taken from the regression standard error (Appendix A). Accuracy analysis is based on the mean, maximum, and minimum standard error (Se) of the predicted temperatures in this study.

Table 4-1. Accuracy summaries based on standard error of the predicted temperature (Se (T_{pred})) of 84 pig level air temperature thermistor sensors located in each measurement zone inside the trailer, in accordance with the calibration data over a temperature range from -15°C to 45°C (5-113°F).

Thermistors	Location	Accuracy—Se (T_{pred}) (°C)		
		Mean	Max	Min
CH 1-1 ~ 1-14	Zone 1	0.67	0.82	0.44
CH 2-1 ~ 2-14	Zone 2	0.75	1.40	0.46
CH 3-1 ~ 3-14	Zone 3	0.71	1.20	0.44
CH 4-1 ~ 4-14	Zone 4	0.85	0.95	0.67
CH 5-1 ~ 5-14	Zone 5	0.84	1.58	0.63
CH 6-1 ~ 6-14	Zone 6	0.87	1.19	0.67

Data from Table 4-1 have shown that, the minimum Se (T_{pred}) value of each thermistor set within all zones ranged from 0.44 to 0.67°C (0.8 – 1.2°F), of which thermistors from zone 1 to zone 3 have similar minimum Se (T_{pred}), and thermistors from zone 4 to zone 6, have similar values. The maximum Se (T_{pred}) values of thermistors in each zone ranged from 0.82 to 1.58°C (1.5 – 2.8°F). The mean standard error (Se) of the predicted temperature indicates the accuracy of the temperature sensors. From Table 4-1, the predicted error ranged from 0.67 to 0.87°C (1.2 – 1.6°F) for each thermistor set installed in the trailer.

According to the accuracy information provided from the manufacturer, the mean accuracy of the predicted error is higher than manufacturer declared (± 0.2°C). But based on the objectives and challenges of this observational study (i.e. field observation, environmental challenges, pig destruction, etc.), these predicted error ranges of the sensor applied are considered to be in an acceptable range.

4.1.2 External Environment Sensor Calibration

Three calibrations were performed for the external temperature sensor from the weather station kit mounted at the front deck of the trailer surface. For all three calibrations, the external temperature sensor showed deviations as large as 5°C when the standard temperature was below 0°C, which was included in the outside temperature ranges designed in this study.

Due to the lack of confidence of the external environment sensor, original data recorded by weather station was discarded and replaced by outdoor temperature and relative humidity data derived from national weather station database and corresponding transport location data derived from GPS sensor for all analyses that include external environment data. More external environment sensor calibration information is included in Appendix B.

4.2 Overall Characteristics of Trailer Thermal Environmental Data

4.2.1 Monitoring Trip Completion Summary

With trailer management based upon the TQA guidelines (Table 3-2), 43 monitoring trips were completed from May 2012 to February 2013. Of these, 31 were classified as TQA typical trips and 12 as alternative boarding trips. One of the TQA typical trips experienced air temperature sensor failures. The results presented in the following sections include only the completed (30) TQA typical and the 12 alternative monitoring trips for analysis considering air temperature and THI assessment, and excludes the 1 trip that experienced air temperature sensor failures. For 85% of the monitoring trips, 93 – 95% of the data collected were viable measurements. For the other 15% of monitoring trips, a greater sensor failure was experienced, resulting in 75 – 77% complete datasets. Analyses including only the data set of 42 monitoring trips were: overall thermal comfort analysis, zone-specific skin temperature distribution, and trailer interior temperature and THI distribution. All 43 monitoring trips were included in analyses of transport duration, floor temperature distribution, and effects of trailer bedding depths and boarding percentages on skin temperature measurement. Over each multi-day monitoring period, 5-7 consecutive trips were conducted in cooperation with the transport company. Summary tables of the TQA typical and alternative arrangements for monitoring and the numbers of completed trips corresponding to specific temperature ranges are included below (Tables 4-2 and 4-3).

Table 4-2. Summary of external environmental and trailer management guidelines evaluated for 31 completed monitoring trips according to TQA protocol.

Temperature [ºC (ºF)]	Trailer Managements			Number of Completed Loads
	Bedding	Boarding	Misting	
< -12 (10)	Heavy	90% with Bottom Covered		4*
-12 to -7 (10-19)	Heavy	75% Evenly Distributed		1
-7 to -4 (20-39)	Heavy	50% Evenly Distributed		3
4-9 (40-49)	Heavy	25% Evenly Distributed		3
10-20 (50-69)	Medium	0%	No Misting	6
21-26 (70-79)	Medium	0%	No Misting	2
27 - 31 (80-89)	Medium	0%	Misting after Loading	3
	Medium	0%	Misting during Loading	3
	Light	0%	No Misting	1
> 32 (90)	Light	0%	Misting after Loading	3
	Light	0%	Misting during Loading	2
			Total	31

* For the outside temperature range <-12°C (10°F), one load experienced air temperature sensor failures and was excluded from analysis involving air temperature assessment.

Table 4-3. Summary of external environment and trailer management guidelines for 12 completed monitoring trips with variations from typical TQA protocol for boarding distribution quantity.

Temperature [ºC (ºF)]	Trailer Managements			Number of Completed Loads
	Bedding	Boarding	Misting	
-7 to -4 (20-39)	Heavy	50% Boarding, More towards Rear	No Misting	3
	Heavy	50% Boarding, All at Rear	No Misting	3
4-9 (40-49)	Heavy	50% Boarding, Evenly Distributed	No Misting	3
	Heavy	25% Boarding, more towards Rear	No Misting	3
			Total	12

4.2.2 Overall Dead or Down Summary

For all 43 monitoring trips, the number of dead or down pigs upon arrival (DOD), corresponding location, and specific outdoor conditions and trailer management is summarized in Table 4-4.

Table 4-4. Summary of pigs dead or down (DOD) for all monitoring trips with trailer managed according to TQA guidelines.

Outside Temperature [°C (°F)]	Trailer Management	Transport Duration (hr)	Pig Skin Temperature		DOD *(n)	Correspo-nding Location
			min (°C)	max (°C)		
-7~4 (20-39)	Boarding, 50% More Towards Rear	2.4	11.6	31.0	1[A]	Zone 6
4-9 (40-49)	Boarding, 25% Evenly Distributed	2.5-3.0	14.3-19.6	30.7-34.5	2[A, 1]	Zone 2
27-31 (80-89)	No Misting	1.6	30.5	39.4	1[B]	Unknown [2]
> 32 (90)	Misting, during loading	3.1	15.5	40.2	1[A]	Zone 6

* For the value in this column, a superscript A indicates it was a dead pig, and a superscript B indicates it was a down pig.
[1] These two dead pigs were observed in different trips.
[2] The pig was able to walk at the beginning of the unloading period, and was documented as downed when it could no longer stand on its own, thus its original location during the transport was not determined.

Over all 43 monitoring trips observed, five total pigs were dead or down (DOD) upon arrival at the abattoir (approximately 0.06% of the total pigs transported). The occurrences of DOD were not concentrated for any outdoor condition or management strategy. Of all five trips that encountered DOD pigs, one trip failed to identify the corresponding location for the down pig during transport, while two of the dead occurrences were in Zone 6 and two were in Zone 2.

4.2.3 Duration of Transport Phases with Pigs on the Trailer

Figure 4-1 represents the distribution of road-transport duration with pigs on the trailer for three events: *before transport*, *during transport* and *after transport*. The y-axis of , 4-1 corresponds to the three events, and the x-axis corresponds to the duration of each event shown in hours.

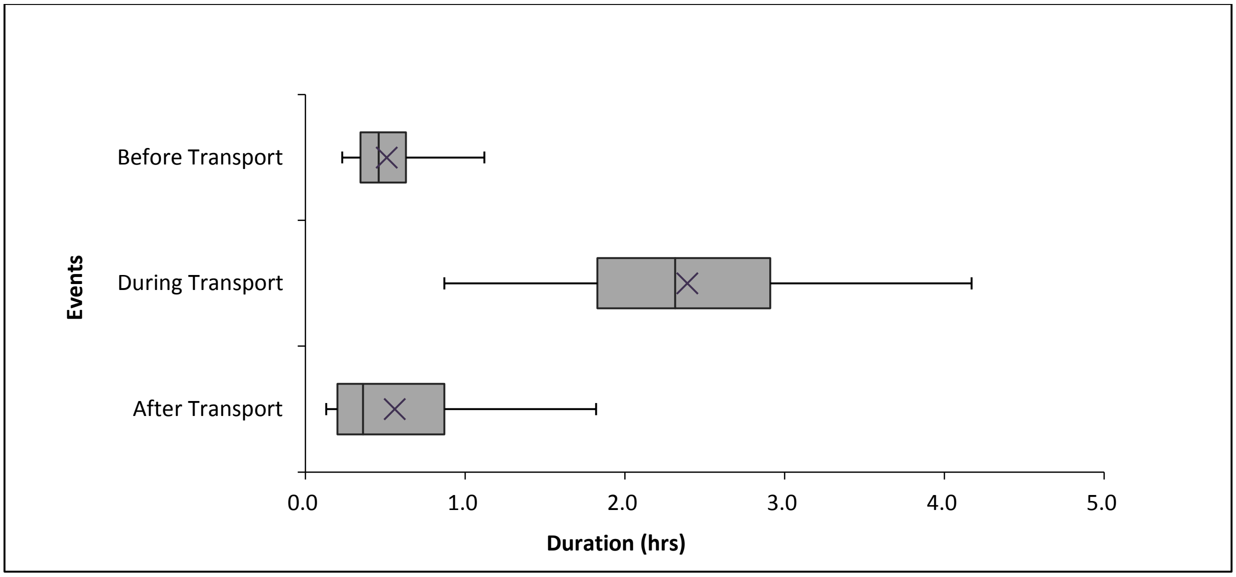

Figure 4-1. Distribution of event durations with pigs on the trailer, including before transport, during transport and after transport for all 43 monitoring trips. In the box and whisker plot, X indicates the mean duration for each event, and the box and whiskers indicate the 0, 25, 50, 75, and 100 frequency percentiles.

For all 43 monitoring trips evaluated, the road-transport duration ranged from 0.2 hr to 1.5 hr, with a mean value of 0.6 h for *before transport* period. The distribution of road-transport duration ranged from 0.8 hr to 4.2 hr, with a mean value of 2.5 hr. For the *after transport* period, the road-transport duration ranged from 0.1 hr to 1.9 hr, while the mean value was 0.6 hr.

The difference in the road-transport duration among *before transport*, *during transport* and *after transport* was primarily due to the broad geographical distribution of swine barns in Midwestern U.S.A, and the distance between them and the processing abattoirs. According to previous studies, shorter transport duration (≤3 hr) can result in more negative effects concerning pig well-being during road transportation compared to longer duration transport (>3 hr) (Sutherland et al., 2009a; Ritter et al., 2009a; Rademacher and Davies, 2005). Based on data derived from the above analysis, for 75% of the events the road-transport duration for *during transport* period fell within the range between 1.0 hr and 2.9 hr, and for 25% of the events the road-transport duration exceeded 2.9 hr. For short road-transport duration, there is a potential for a greater mortality during transport and more downed pigs upon arrival at the abattoir. Nevertheless, as the monitoring trips in this study were scheduled according to the regular routines of typical swine transportation in Midwestern U.S.A, the duration of the road-transport, while an important factor, is hard to control or manipulate.

4.2.4 Overall Thermal Conditions

Of all 42 completed monitoring trips, 20 trips were classified as warm/ hot-temperature trips, and 22 trips were classified as cool/cold-temperature trips. Of the trips evaluated, a broad range of temperature and temperature-humidity index levels were measured, according to classification ranges specified in section 3.7.1.2 (Tables 4-5 and 4-6).

Table 4-5. Assessment of trailer environment based on categorizing all 84 pig-level air temperature measurements and their locations into thermal comfort classifications for all transport duration with pigs on the trailer. Data include all 42 monitoring trips during hot, mild and cold conditions. A colored block indicates the condition occurred at some point during one of the loads monitored. The top number inside the colored block indicates the number of loads experiencing this condition. A single trip may experience multiple ranges of thermal comfort. The bottom number represents percentage of time each trip spent at this condition, with the range covering all trips for the given arrangement.

Temperature (°C)(°F)	Trailer Management			Completed Trips	Thermal Comfort Ranges						
	Bedding	Boarding	Misting		Extreme Cold[1]	Cold[2]	Cool[3]	Thermo-neutral[4]	Warm[5]	Hot[6]	Extreme Hot[7]
< -12 (10)	Heavy	90%, with bottom open		3	3 (0.1% - 3.4%)	3 (15.1% - 53.7%)	3 (43.3% - 83.2%)	1 (1.6%)			
-12 ~ -7 (10-19)		75%, Evenly Distributed		1	1 (0.5%)	1 (43.2%)	1 (55.6%)	1 (0.4%)			
-7 ~ 4 (20-39)	Medium	50%, Evenly Distributed		3		2 (0.4% - 10.2%)	3 (89.8% - 91.4%)	2 (8.2% - 9.0%)			
		50%, More Towards Rear		3		2 (0.2% - 1.4%)	3 (98.0% - 100%)	2 (0.3% - 0.6%)			
		50%, All at Back		3			3 (95.4% - 100%)	2 (0.9% - 4.6%)			
4 - 9 (40-49)	Medium	25%, Evenly Distributed		3			3 (87.4% - 100%)	2 (3.5% - 12.6%)			
		50%, Evenly Distributed		3		1 (0.3%)	3 (84.4% - 98.5%)	3 (1.2% - 15.6%)			
		25%, More Towards Rear		3			3 (84.3% - 98.8%)	3 (1.2% - 15.7%)			
10 - 20 (50-69)	Medium		No Misting	6			6 (0.2% - 97.1%)	6 (2.9% - 91.4%)	5 (0.1% - 8.4%)	1 (0.2%)	
21 - 26 (70-79)	Medium		No Misting	2			1 (0.7%)	2 (69% - 93.4%)	2 (5.9% - 30.4%)	1 (0.6%)	
26 - 32 (80-89)	Medium		Misting After Loaded	3			1 (1.0%)	3 (7.3% - 82.9%)	3 (16.1% - 70.3%)	2 (3.9% - 41.1%)	1 (24.1%)
			Misting During Loading	3			1 (1.8%)	3 (1.0% - 24.1%)	3 (50.4% - 98.6%)	3 (0.4% - 25.5%)	
			No Misting	1			1 (0.4%)	1 (1.8%)	1 (67.0%)	1 (30.8%)	
>32 (90)	Light		Misting After Loaded	3				2 (0.1% - 0.3%)	3 (0.7% - 1.7%)	3 (57.9% - 79.4%)	3 (19.3% - 41.0%)
			Misting During Loading	2				2 (0.4% - 0.5%)	2 (4.3%-4.7%)	2 (26.3% - 32.6%)	2 (62.7% - 68.5%)

[1]Extreme Cold: T_{in} < -15°C (5°F); [2] Cold: -15°C (5°F) < T_{in} < 0°C (32°F); [3] Cool: 0°C (32°F) < T < 18°C (62°F); [4] Thermoneutral: 18°C (62°F) < T < 25°C (77°F);

[5] Warm: 25°C (77°F) < T < 30°C (86°F); [6] Hot: 30°C (86°F) < T < 35°C (95°F); [7] Extreme Hot: T > 35°C (95°F).

For the 20 warm/hot-temperature trips evaluated (Table 4-5), there were 17 trips in which pigs experienced warm temperatures, 12 trips in which pigs experienced hot conditions, and 6 trips in which they experienced extreme hot conditions. Furthermore, cool conditions were observed inside the trailer for 10 trips of the 20 warm/hot-temperature trips evaluated. For the 6 trips determined as extreme hot trips, the frequency of occurrence of extreme hot conditions experienced by the pigs ranged from 19.3% to 68.5%. Specifically, for outside temperature above 32°C (90°F), the range of frequency of occurrence observed was as high as 62.7% to 68.5%, which indicates that more than half of the time × location measurements recorded extreme hot conditions on the trailer during these trips.

Table 4-6. Assessment of trailer environment based on categorizing all pig-level air temperature and zone-centered environmental measurements, and their locations into Livestock Weather Safety Index (LWSI) for all transport duration when pigs were on the trailer. Data included 20 monitoring trips during hot weather. A colored block indicates the condition occurred at some point during one of the loads monitored. The top number inside the colored block indicates the number of loads experiencing this condition. A single trip may experience multiple ranges of thermal comfort. The bottom number of the last two columns represents percentage of time each trip spent at this condition, with the range covering all trips for the given arrangement.

Temperature (°C)(°F)	Misting Arrangement*	Bedding Arrangement	Completed Trips	Livestock Weather Safety Index Categories			
				Normal[1]	Alert[2]	Danger[3]	Emergency[4]
10-20 (50-69)	None	Medium	6	6	2	1 (0.3%)	1 (0.1%)
21-26 (70-79)	None	Medium	2	2	2	1 (1.2%)	
26-32 (80-89)	After Loading	Medium	3	3	3	3 (1.3 - 32.8%)	2 (0.8 - 3.9%)
	During Loading	Medium	3	3	3	3 (1.0 - 35.6%)	2 (0.2 - 0.5%)
	None	Medium	1	1	1	1 (1.3%)	
>32 (90)	After Loading	Light	3	3	3	3 (47.7 - 74.8%)	3 (0.6 - 23.8%)
	During Loading	Light	2	2	2	2 (32.6 - 61.9%)	2 (33.0 - 63.7%)

*: No boarding was applied during warm temperatures

[1]Normal: THI < 74; [2]Alert: 74 < THI < 78; [3]Danger: 78 < THI < 84; [4]Emergency: THI > 84

In terms of LWSI (Table 4-6), during the 20 warm/hot-temperature trips, pigs encountered some normal conditions for each trip. For 16 trips they encountered alert conditions, for 14 trips they encountered danger conditions, and emergency conditions occurred in 10 of the 20 trips. When ambient temperature exceeded 21°C (70°F), 9 of the 14 trips encountered emergency conditions, even though no extreme hot temperature was reported inside the trailer for 4 of those emergency trips. In searching for the best method to assess multiple environmental conditions in the same analysis, LWSI was chosen as the best option despite its development for cattle. No appropriate pig-based options were identified. The categories of LWSI may not truly reflect emergency or danger status for pigs during transport, but provides a comparative assessment of THI within the trailer. LWSI also neglects air velocity, which is an important factor for pig thermal status.

For comparing the two misting approaches in the hottest conditions, extreme hot temperature conditions and emergency LWSI were observed during both misting approaches. When ambient temperature exceeded 32°C (90°F), 5 trips experienced emergency LWSI conditions. For misting after loading, the frequencies of occurrences for emergency LWSI conditions ranged from 0.6 to 23.8% for 3 monitoring trips; while for misting during loading method, they ranged from 33.0 to 63.7% for 2 monitoring trips. Because there were no monitoring trips completed with no misting arrangement when outside temperature ranged from 26 to 32°C (80 to 89°F), this combination cannot be considered in comparison to the two misting approaches that were applied. These results indicate that misting during loading may have the potential to create a dangerous condition for the pigs with the additional moisture.

Likewise, for the 22 cool/cold-temperature trips evaluated, there were 12 trips in which pigs experienced cold temperatures, all 22 trips in which pigs experienced cool temperatures, and 4 trips in which they experienced extreme cold temperatures. For the 4 monitoring trips determined as extreme cold trips, the frequency of occurrence of extreme cold conditions experienced by the pigs ranged from 0.1% to 3.4%.

Based on the results of this overall summary, pigs experienced undesirable temperature conditions when ambient temperature exceeded 27°C (80°F) or was less than 5°C (40°F). Moreover, compared to cold stress conditions during transport, pigs had more potential to experience heat stress for greater durations when outside temperature became extreme during hot weather conditions. Results shown in Tables 4-5 and Table 4-6 do not indicate potential problem areas inside the trailer, which justifies the need for a more complete analysis to determine the locations within which the thermal environmental extremities occurred.

4.2.5 Temperature Distribution inside the Trailer

Figures 4-2, 4-3 and 4-4 show three screen captures from two animations of temperature distribution during two different monitoring trips. Animations were created to demonstrate temperature patterns within the trailer during the loading period at the swine barn, during the transport period, and prior to unloading when the trailer was stopped at the abattoir. The range of temperatures provides insight into airflow patterns within the trailer. The snapshots represent the pig-level air temperature distribution of trailer top and bottom levels at a time when misting was applied during the loading period at the swine barn. The corresponding monitoring trips were both categorized as extreme hot-temperature trips in which the ambient temperature range was above 32°C. In the animation, red indicates hotter temperatures and blue indicates cooler temperatures, and the green dots indicate the pig-level air temperature sensors. Temperature data between sensors were generated using linear interpolation.

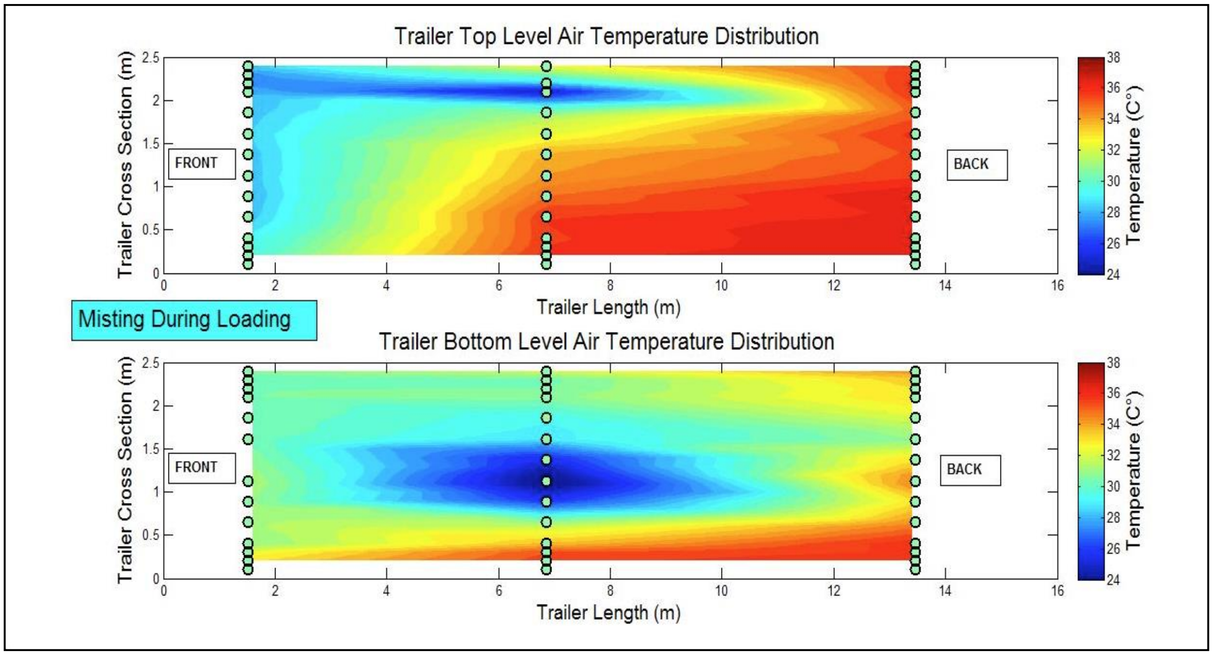

Figure 4-2. Temperature distribution at one point in time from an animation of a monitoring trip when misting was applied during the loading period while the trailer was stopped at the swine barn. The corresponding monitoring trip was categorized as an extreme hot-temperature trip for which the ambient temperature range was above 32°C. In the animation, red indicates hotter temperatures and blue indicates cooler temperatures, and the green dots indicate the pig-level air temperature sensors.

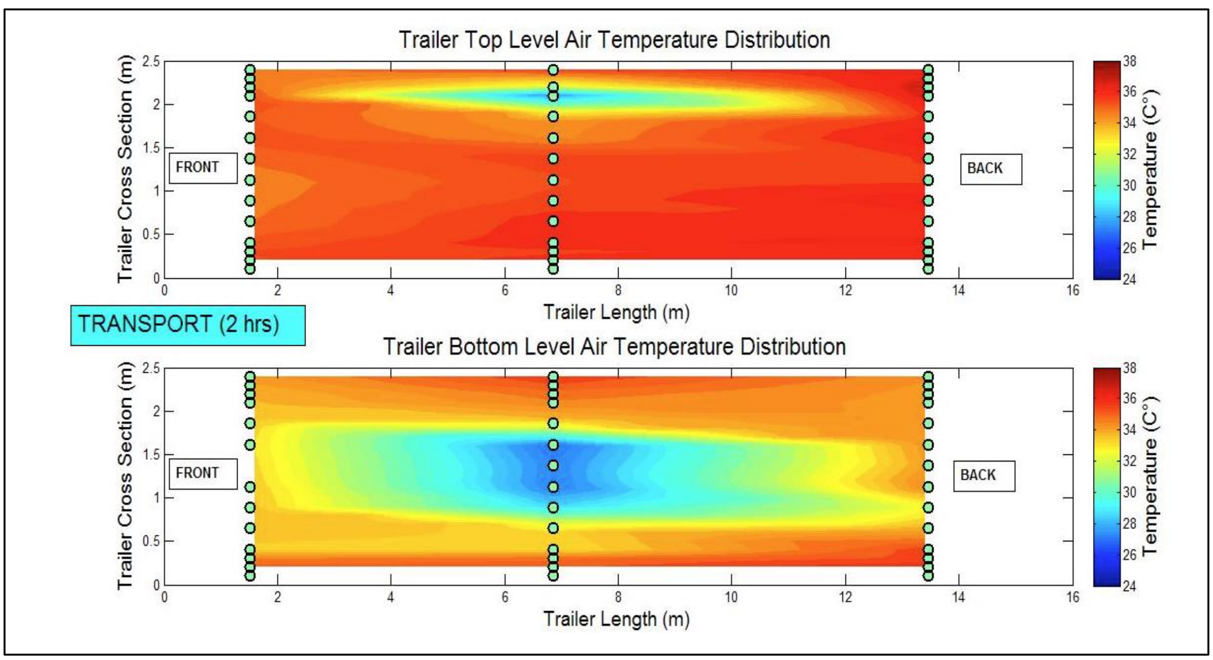

Figure 4-3. Temperature distribution at one point in time from an animation of a monitoring trip after 10 minutes elapsed since transport started after misting during loading for 60 minutes at swine barn. The corresponding monitoring trip was categorized as an extreme hot-temperature trip for which the ambient temperature range was above 32°C. In the animation, red indicates hotter temperatures and blue indicates cooler temperatures, and the green dots indicate the pig-level air temperature sensors. Lighter color areas in this figure represent the cooling effects that lasted into the transport period after 10 minutes road-transport.

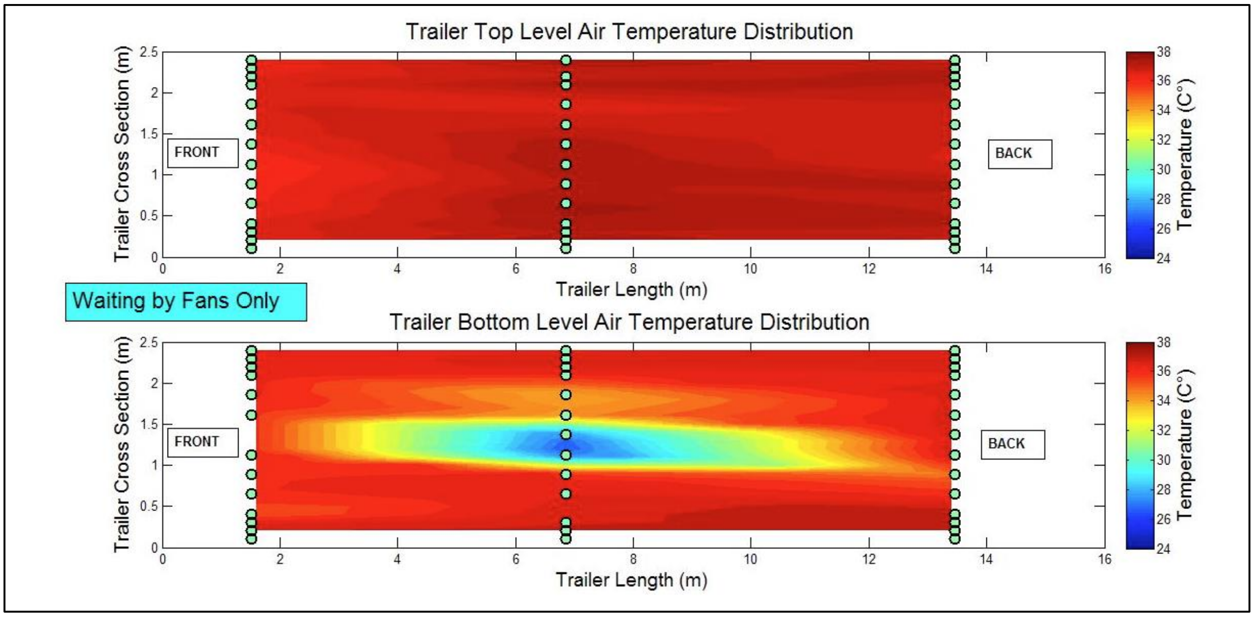

Figure 4-4 Temperature distribution at one point in time from an animation of a monitoring trip when the trailer was stopped at the abattoir with external fans after 13 minutes' external fans with internal misting from the previous waiting session. The corresponding monitoring trip was categorized as an extreme hot-temperature trip for which the ambient temperature range was above 32°C. In the animation, red indicates hotter temperatures and blue indicates cooler temperatures, and the green dots indicate the pig-level air temperature sensors.

Animations also helped to better understand the complexities of the air movement within the trailer and to supplement the information attained in the overall summaries for the different management scenarios observed. In general, lower temperatures near the openings were assessed as inlets and higher temperatures as outlets due to the warming of the air by the pig heat production, with the exception that misting also created cooler areas within the trailer. This approach allowed a rudimentary assessment of ventilation inlets and outlets. Temperature distribution patterns in the animations demonstrated that the ventilation patterns did not follow the same trend for all monitoring trips, which is contrary to previous results generalized by Ellis et al. (2008), who concluded that for a moving trailer in hot weather, the rear and some of the middle section of the trailer constituted the ventilation inlet and the front would be ventilation outlet. In their study, a straight-deck trailer was divided into two levels with five compartments on the top level and six compartments on the bottom level. A custom-designed sensor pack included an air temperature thermistor, an anemometer, a temperature/RH sensor, and a carbon dioxide sensor was installed in the center of each compartment to capture the compartment-centered air temperature, air velocity, and carbon dioxide concentration. The contradiction between the two studies could be hypothetically explained by different trailer designs and managements, distinct distribution of sensor location, various external weather conditions, or trailer velocity. Further research would be necessary to better understand the influences on ventilation patterns during transport.

As seen in the screen captures corresponding to the animation, the air temperature distribution inside the trailer was not uniformly distributed. The cooling effects of misting were concentrated along the right side length of the trailer on the top level and in the middle area of the trailer on the bottom level. With a bank of fans operating external to the stationary trailer at the abattoir, cooling effects of fan operation were not observed for the top level of the trailer, and cold air temperature that can cause chilled pigs was observed in the lower level, despite a high ambient temperature of 35°C (95°F) (Figure 4-4). This indicates that the fans were likely not moving air for the top level of the trailer. The screen captures and the complete animations illustrate that the non-uniform thermal patterns apparently resulted from varying inlet and outlet locations around the perimeter of the trailer, unequally distributed misting nozzles across the width of the trailer, the limited effectiveness of the fans at the abattoir. The effectiveness of the fans may be impacted by the intensity of fan operation, the operating height of the fan banks, the duration of fan operation, and the intermittency of fan and misting operation.

4.2.6 Overall Zone-specific Skin Temperatures

Figure 4-5 demonstrates the overall frequency of occurrence for the zone location of the maximum and minimum pig skin temperatures for all the 43 monitoring trips. Over all of the observations, 33% of the trips observed the maximum skin temperature in Zone 3, and 49% of the trips observed the maximum skin temperature in Zone 6, for a total frequency of 82% of the trips evaluated (35 out of 43 monitoring trips) with maximum skin temperature in the rear sections of the trailer. For other locations inside the trailer, the frequencies of occurrence for the maximum skin temperature were 17% for the front sections, and 2% for the middle sections of the trailer, respectively.

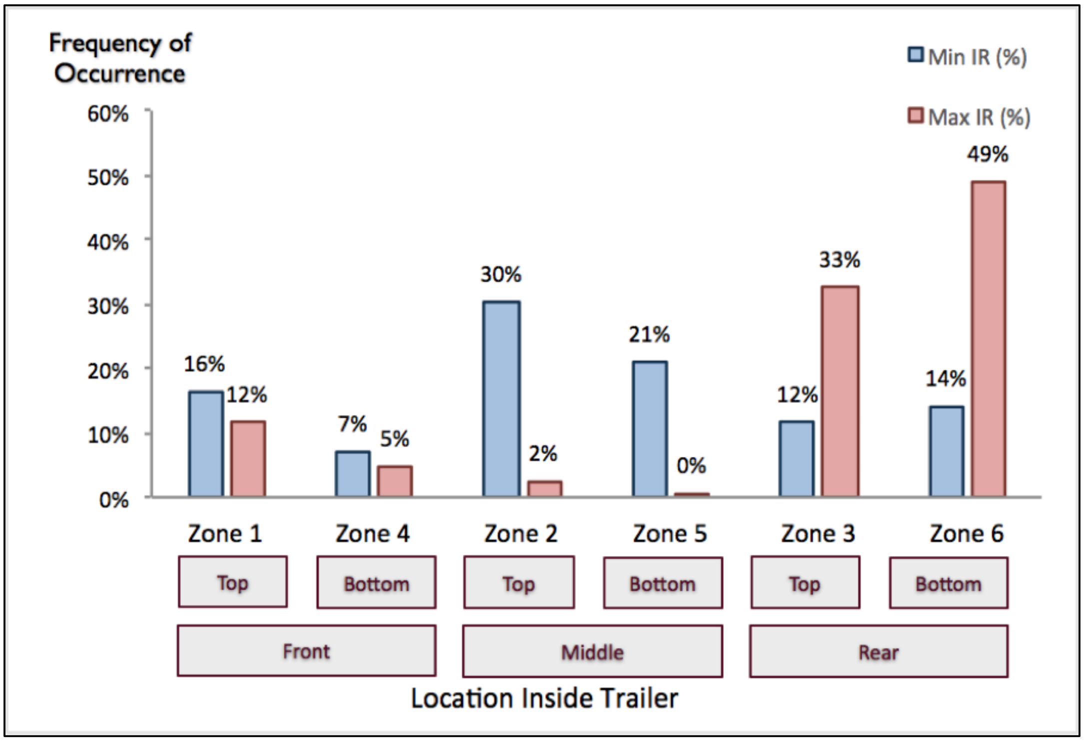

Figure 4-5 Location of maximum and minimum skin temperatures (represented by IR) within the trailer for 42 monitoring trips over outside temperatures ranging from -14 to 38°C (7 to 100°F). The rear compartments consistently resulted in the warmest skin temperatures on the trailer, and the middle compartments frequently resulted in the coolest skin temperatures on the trailer, regardless of outdoor weather conditions. The same general trend was observed when this figure was broken out by thermal comfort ranges and boarding percentages.

For locations of the minimum pig skin temperature, 30% of the trips observed the minimum in Zone 2, and 21% the trips observed the minimum in Zone 5, for a total of 51% of the trips evaluated (21 out of 43 monitoring trips) with the minimum skin temperature in the middle sections of the trailer. For other zones inside the trailer, of 23% of the trips evaluated, the minimum pig skin temperature was reported in the front sections of the trailer, and of 26% of the trips evaluated, the minimum pig skin temperature occurred in the rear sections of the trailer.

This analysis of the most extreme conditions within the trailer revealed that the pigs in the rear sections of the trailer experienced the highest skin temperatures, and those in the middle sections within the trailer encountered the lowest skin temperatures. This overall analysis does not consider whether or not these extremes crossed any dangerous thresholds for the pigs. It combines all 43 monitoring trips over the broad outside temperature monitored, and it is important to further break the above analyses into warm/hot-temperature trips and cool/cold-monitoring trips for better categorization and understanding of the severity of the potential problem areas inside the trailer.

4.2.7 Overall Floor Temperature Distribution

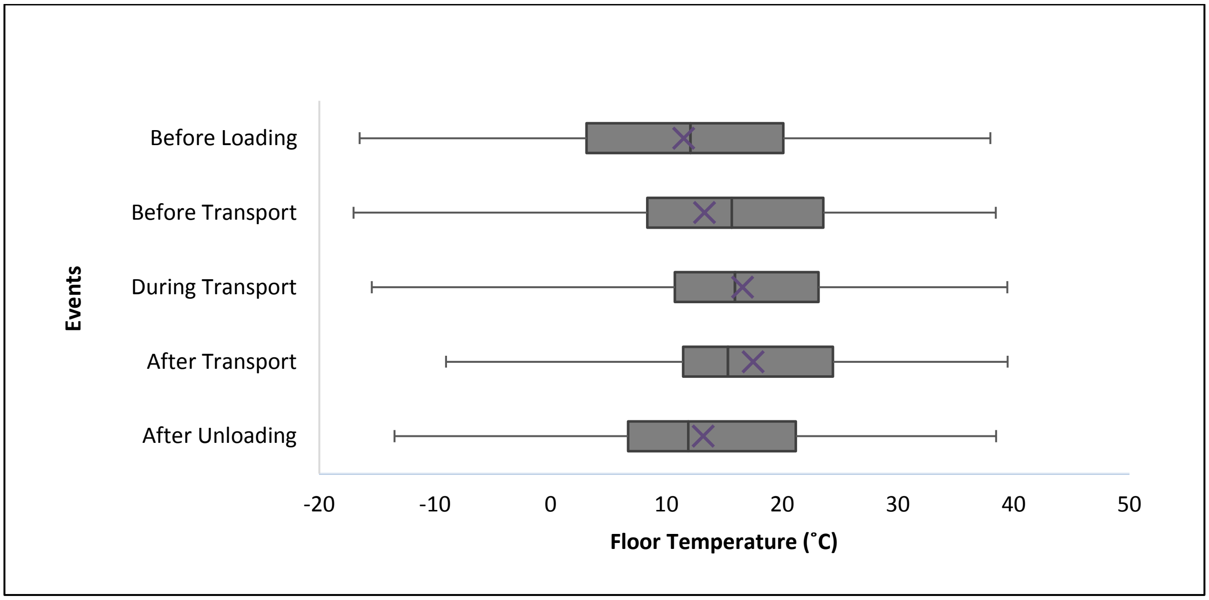

Figure 4-6 Overall distribution of averaged floor temperature from each trip for before, during, and after pigs were on the trailer for all monitoring trips. X indicates the average value of floor temperature, and the box and whiskers indicate the 0, 25, 50, 75, and 100 frequency percentiles.

Of the 43 monitoring trips evaluated, the overall floor temperatures ranged from -18°C to approximately 40 °C (0 to ~100°F). Not surprisingly, there was an increase in the average floor temperature with pigs on the trailer continuing through to the period just after unloading, likely because of the heat contribution of the pigs to the space, and dropping after then.

This overall floor temperature distribution analysis revealed that on average, pigs experienced a warm to hot floor/bedding temperature within the trailer during warm to hot weather conditions, while some pigs experienced frozen bedding and floors at some point during cold weather transport. These undesired conditions may be explained by unevenly distributed temperatures inside the trailer, variable bedding depth, and the difficult but important task of controlling moisture during freezing outdoor temperatures. The analysis also reveals the need to further explore these extreme conditions to further characterize and assess the severity of the problem.

4.2.8 Effects of Trailer Bedding Depth on Skin Surface Temperature

The effects of light, medium, and heavy bedding (described in section 3.4.2) on pig's skin surface temperature were evaluated and summarized in Figure 4-7. Of all 43 trips observed, the effects of trailer bedding depth on pig skin temperature were first characterized by the relation between pig skin temperature and the zone-centered air temperature recorded in the corresponding location and time, including *before transport*, *during transport*, and *after transport*. In Figure 4-7, the pig skin temperature is plotted against the corresponding zone-centered air temperature, and the assessed trailer bedding depths are demonstrated by different shaped symbols.

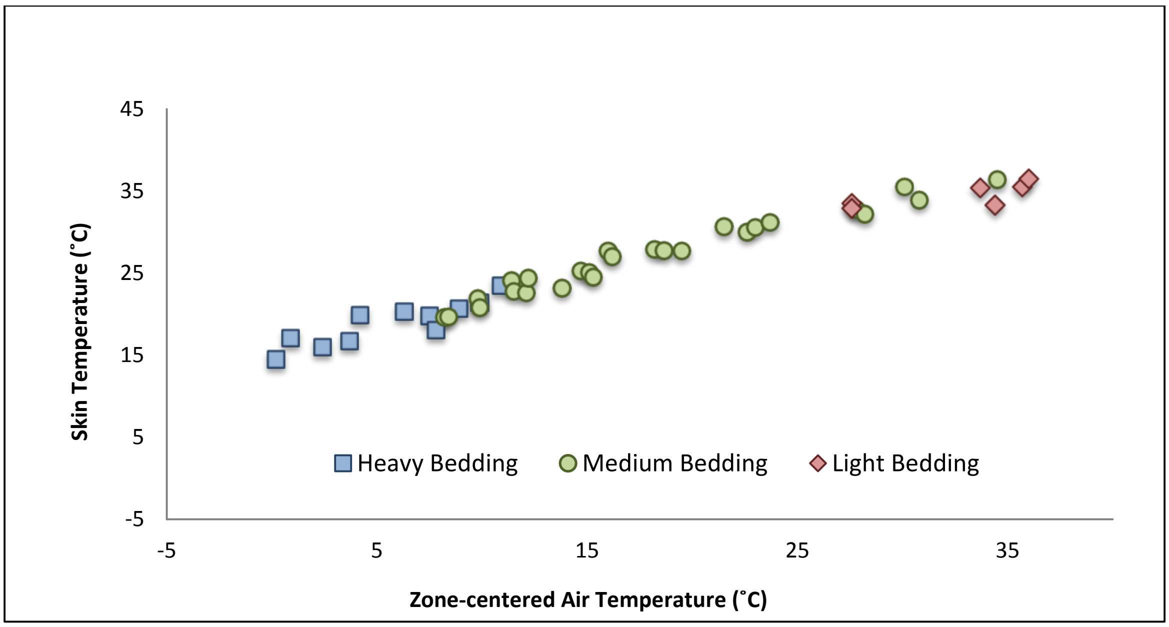

Figure 4-7 Skin surface temperature versus corresponding zone-centered air temperature taken for different bedding depths, including measurements taken before transport, during transport and after transport during 43 monitoring trips over temperatures ranging from -14 to 38°C.

The scatterplot shown in Figure 4-7 depicts a linear relation between pig skin temperature and the corresponding zone-centered air temperature. As zone-centered temperature increased with the ambient air temperature, the skin temperature of the pigs experiencing that temperature also increased, regardless of different trailer bedding depths used.

If the bedding affected the skin temperature, a temperature gradient between the three bedding depths would be expected. Based upon these results, pig skin temperature measurement was linearly related to the corresponding zone-centered air temperature, there is no evidence to support the notion, and the different bedding depths evaluated did not seem to provide extra thermal insulation to the pigs. This result agrees with a recent study conducted by McGlone et al. (2013). In their study, the environmental management during transport was evaluated for market pigs, of which the effects of 6 randomly assigned bedding coverage (3, 5, 6, 7, 9, and 12 bags of bedding materials, respectively) on thermal environment were assessed for outside temperature ranged from -13 to 45°C (8 to 113°F). Depth of bedding, trailer interior air temperature, and the interaction of bedding and air temperature on DOA, NA and DOD were recorded and assessed with regression models. Of a total number of 1,344 trips studied, their results revealed no advantage for added more than 6 bags of bedding during cold weather [T_{out} <0°C (32°F)], or more than 3 bags during mild weather [0°C < T_{out} < 21°C (32°F < T_{out} < 70°F)]. An increase in the DOA rate was recorded for adding more than 3 bags of bedding for warm weather [T_{out} > 21°C (70°F)]. Their results also showed that the skin temperature of pigs exiting the trailer changed with air temperature and had no dependence on trailer bedding depth. Note that their measurement method and location were very different from that in this study. Additionally, the skin temperature measured in this study was taken above the pigs as opposed to below where the bedding was located. So, the result represented here indicated that the bedding did not affect the overall environment of the trailer, but any effect on the micro-environment near the pig surface facing the floor was not represented with our data. Effects from this would have been expected to be represented by floor temperature, which also did not reveal any effects of bedding depth.

The importance of ambient conditions on pig skin temperature is highlighted through the linear relationship between the air and skin temperatures and should be considered when making decisions of trailer management during transport. Additionally, using skin temperature as an indicator of the thermal environment is an acceptable approach for transport environment assessment.

4.2.9 Effects of Boarding Percentage on Pig Skin Temperature Measurements

The overall effect of trailer boarding variations on pig skin temperature was assessed for all 43 monitoring trips and summarized (Figure 4-8). In Figure 4-8, the maximum and minimum pig skin temperatures are plotted against the corresponding zone-centered air temperatures observed for the same location and time (as described in section 3.6.1.1). Different shaped symbols (squares and circles) are applied to represent the maximum and the minimum pig skin temperatures, and the corresponding symbols with different colors demonstrate trailer boarding percentages varied from 0 to 90%. The average pig skin temperature is also represented in the figure as a reference.

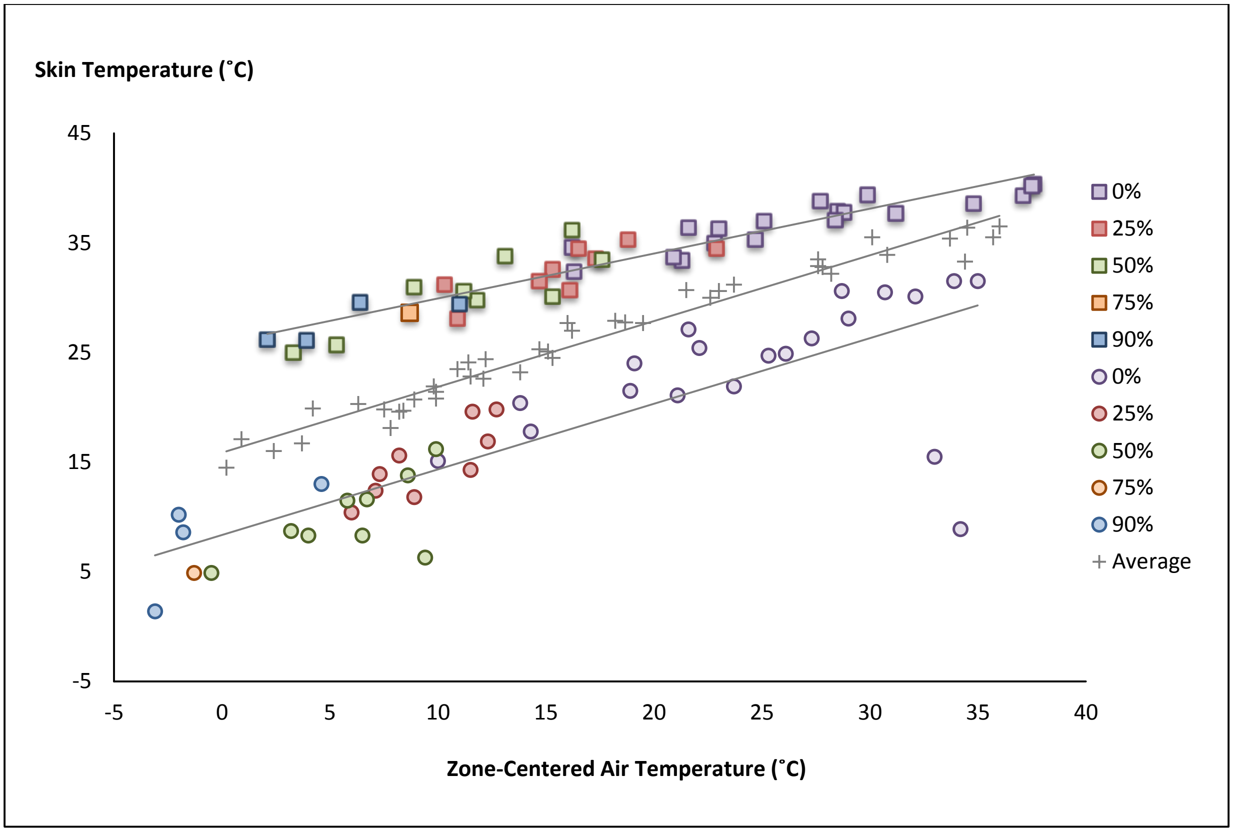

Figure 4-8 Overall effects of trailer boarding variations (including 0-90%) on pig skin temperatures during transport. The maximum and minimum skin temperatures (represented by squares and circles) are plotted against zone-centered air temperature. Different trailer boarding variations are represented by identical shapes with different colors. The average skin temperature is included on the figure as a reference.

As shown in Figure 4-8, no obvious effects on pig skin temperature measurements can be seen for different trailer boarding percentages. As zone-centered air temperature increases, both the minimum and the maximum pig skin temperatures increase, and tend to converge when zone-centered air temperature become more extreme. Note that two outliers are identified for 0% trailer boarding percentage when the corresponding zone-centered air temperature were approximately 34°C (93°F), and each of the corresponding trips was monitored with one of the misting approaches. Therefore, the outliers possibly resulted from cooled sensors from misting, or plausible sensor malfunction. For the overall perspective, pig skin temperature is linearly related to the corresponding zone-centered air temperature, and is generally not dependent on trailer boarding percentage. For minimum skin temperatures at colder air temperatures, the relationship is less distinct, which may be an indication that trailer boarding has an impact under these conditions.

These results further agree with the results discussed in 4.2.7, and indicate that zone-centered air temperature is a good indicator for pig skin temperature and vice versa. This overall analysis was developed for all trips and all trailer boarding variations, and it is important to further analyze the effectiveness of boarding for alleviating cold conditions, where skin temperatures near freezing were observed.

4.2.10 Effects of Short Breaks during Transport on Trailer Thermal Environment

The effects of short breaks on trailer thermal environment during transport with pigs present on the trailer for one monitoring trip during mild weather conditions [21 to 26°C (70 to 80°F)] was explored and summarized in Figure 4-9.

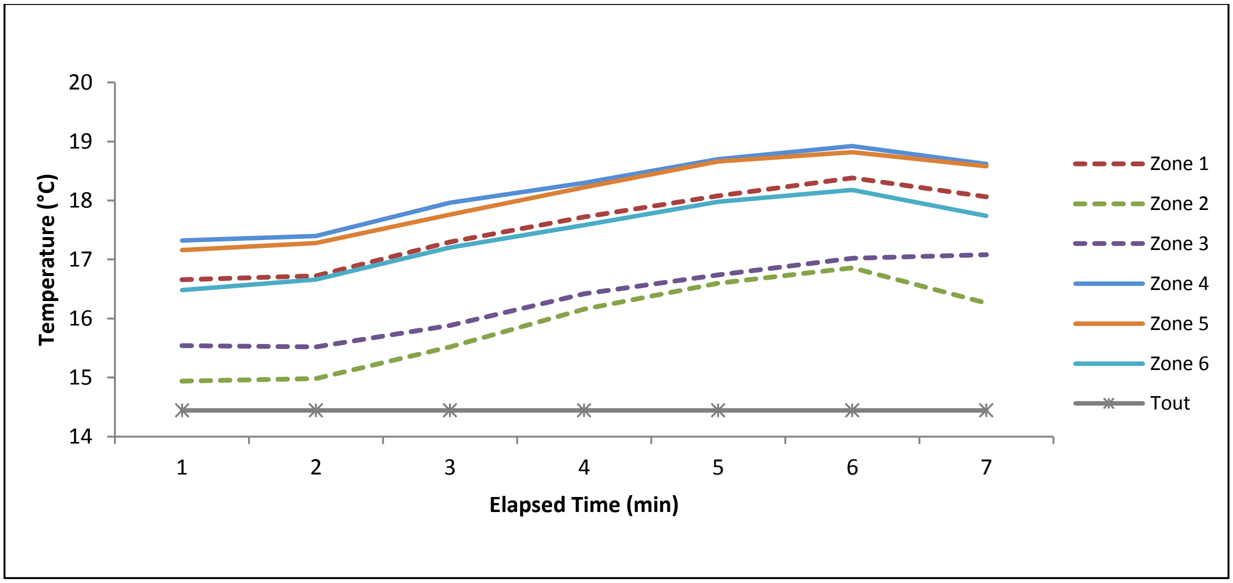

Figure 4-9. Trailer interior zone-centered air temperature and outside temperature change during mild ambient weather conditions (21 to 26°C) during short breaks with pigs present on the trailer for during transport period.

From Figure 4-9, stopping for breaks resulted in rapid temperature increases for all 6 zones within the trailer, with a temperature rise of almost 1°C/min (1.8°F/min) with a 3-4°C (5-7°F) trailer interior temperature rise in approximately 5 minutes. Based on observations during monitoring trips, this situation happened in cases when trailer stopped for short breaks of more than 5 minutes. For hot weather conditions, even when the total temperature rise within the trailer was limited to 1 to 2°C (2 to 4°F), it caused rapidly changes of thermal conditions to a more dangerous level (i.e. from hot conditions to extreme hot conditions). For mild to cold weather conditions, higher temperature rises [3-4°C (5-7°F) within 5 minutes] were observed throughout the trailer, which alleviated the thermal condition from the previous transport section to a milder level (i.e. from cool conditions to thermoneutral conditions).

Based on these results, brief stops of the trailer should be limited during hot weather conditions, while stopping during cold conditions may have benefit for alleviating some of the cold conditions. The implications of this approach were not explored in this study, such as impacts on gas concentrations or animal fatigue.

4.3 Assessment of Current TQA Guidelines for Hot Weather Conditions

4.3.1 Zone-specific Skin Temperature Responses for Hot Weather Conditions

As described in sections 3.7.1.4 and 4.2.5, the skin temperatures observed within specific zone locations were further examined for hot-temperature trips and extreme hot-temperature trips. Figures 4-10 and Figure 4-11 summarized the frequency of occurrence for the minimum and maximum pig skin temperature within specific zone locations for 20 hot-temperature trips and 6 extreme hot-temperature trips, respectively.

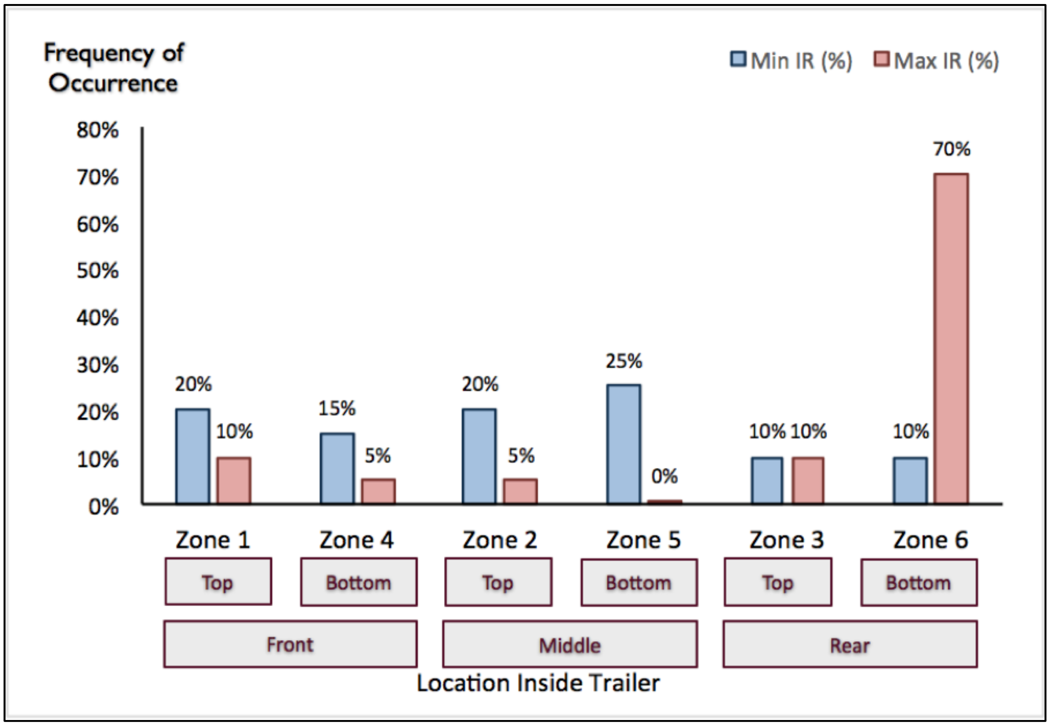

Figure 4-10 Location of maximum and minimum skin temperatures (represented by IR) observed within the trailer during transport for 20 monitoring trips monitored under hot weather conditions (10°C and above). The rear compartments frequently resulted in the warmest skin temperatures on the trailer.

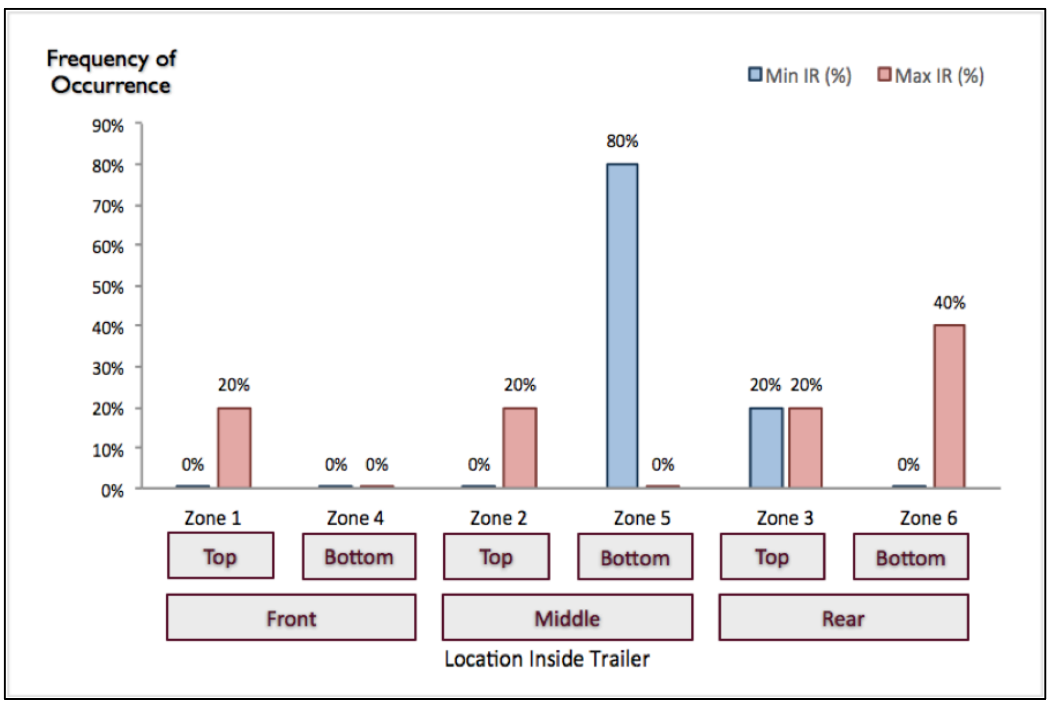

Figure 4-11 Location of maximum and minimum skin temperatures (represented by IR) observed within the trailer during transport for 6 monitoring trips monitored under extreme hot weather conditions (32°C and above). The rear compartments frequently resulted in the warmest skin temperatures on the trailer, and the middle compartments frequently resulted in the coolest skin temperatures on the trailer.

Maximum skin temperature represents the worst-case scenario in hot weather, indicating the zone within the trailer with pigs needing to lose the most heat to the environment for thermoregulation. For the 20 warm/hot-temperature trips evaluated, 70% of the maximum pig skin temperatures were observed in Zone 6, with another 10% in Zone 3, for a total of 80% of maximum skin temperatures occurring in the rear sections of the trailer (16 out of 20 warm/hot-temperature trips). The maximum pig skin temperatures were recorded in the front and middle sections of the trailer 15% and 5% of the trips, respectively. For the 6 extreme hot-temperature trips evaluated, 60% of the trips observed the maximum pig skin temperature in the rear sections of the trailer, with 20% in Zone 3 and 40% in Zone 6. The front and middle sections of the trailer each observed 20% of the maximum skin temperatures.

Minimum skin temperature potentially represents the best-case scenario in hot weather, with the pigs needing to lose the least amount of heat to the environment or experiencing a cooling effect. The majority of minimum skin temperatures were observed in Zone 2 and Zone 5, with 20% and 25% of the 20 warm/hot-temperature trips evaluated, respectively. Thus, for 9 out of 20 trips, the minimum skin temperature was recorded in the middle sections of the trailer. The frequency of occurrence of the minimum skin temperature recorded in the front and rear sections of the trailer were 35% and 20%, respectively. For the 6 extreme hot-temperature trips evaluated, the minimum skin temperature was observed in Zone 5, bottom level zone in the middle section, for 80% of the trips. For the other 20% of the trips, it was observed in Zone 3, top level zone in the rear sections of the trailer.

Based on the results in this section and those presented previously in this report, the locations of the maximum and minimum pig skin temperature followed the same trend for the overall monitoring trips, warm/hot-temperature trips, and extreme-hot temperature trips, with the majority of the maximum skin temperature measurements occurring in the rear sections of the trailer, while the majority of the minimum skin temperatures occurred in the middle sections of the trailer. As discussed in section 1.3, compared to cold stress, heat stress has the potential to increase animal losses, especially during hot weather conditions (Curtis 1983, DeShazer et al. 2009). As indicated in Table 4-5, while only a small portion (< 30% for 63% of the trips evaluated) of duration of transport experienced thermoneutral [$18 < T_{in} < 25°C$ ($65 < T_{in} < 77°F$)], the majority of the trailer experienced warm through hot conditions [$T_{in} > 25°C$ (77°F)]. By observing the majority of warmest skin temperatures occurred in the rear sections of the trailer, it yields a great concern of potential heat stress experienced by the pigs throughout the road-transportation. Realizing that the cooling effects were not uniform throughout the trailer, one approach to alleviate this variability may be to primarily consider the rear sections of the trailer when applying cooling methods to the trailer after transport (i.e. adjust the location of the trailer to keep the rear sections closer to the fan bank, having more misting nozzles in the rear sections, etc.), though this approach was not tested in this study.

4.3.2 Zone-specific THI Distribution inside the Trailer during Hot Weather

Similar to zone-specific skin temperature analysis, 20 warm/hot-temperature trips were analyzed for maximum THI measurements by identifying the corresponding locations within which the maximum THI occurred in the trailer (Figure 4-12).

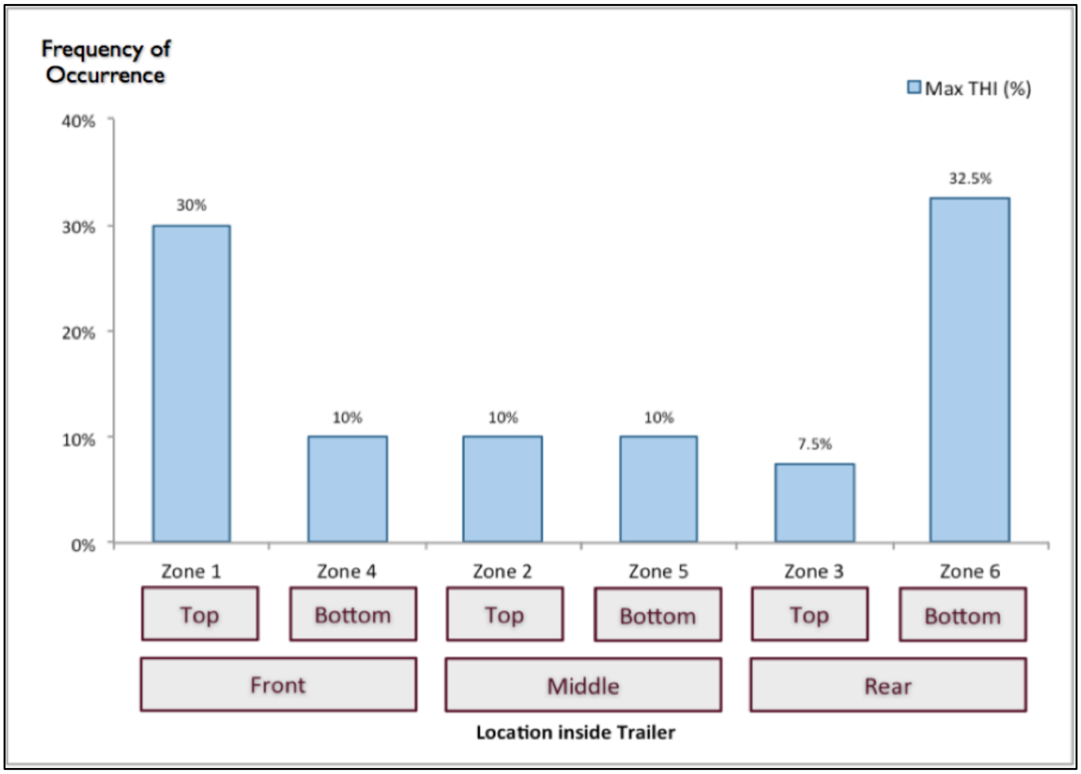

Figure 4-12. Specific zone location of maximum THI in the trailer for 20 hot temperature trips. Zone 1 and Zone 6 resulted in the highest maximum THI measurements.

As shown in Figure 4-12, for 20 warm/hot-temperature trips evaluated, the majority of the maximum THI measurements were recorded in Zone 1 for 30% of the trips evaluated and in Zone 6 for 32.5% of the trips evaluated, indicating that the top-level front zone and the bottom-level rear zone are likely locations challenging for pigs during transport in hot weather.

Combined with the temperature patterns presented in the animations, these results support the suggestion that ventilation patterns were not consistent, and ventilation inlets and outlets were not behaving according to the classical expectations (Ellis et al., 2008; Purswell et al., 2006). Based on the animations, maximum and minimum air and skin temperatures, ventilation inlets appear to be frequently along the middle sections of the trailer with outlets located in the front and the rear.

4.3.3 Effectiveness of Misting Before Transport during Hot Weather

The effectiveness of two different approaches for misting pigs before transport were evaluated by: (1) the animated trailer interior thermal distribution patterns (dry bulb temperature); (2) pig skin temperature reduction between initial and minimum skin temperature; and (3) the time duration elapsed between critical skin temperatures (as described in section 3.7.2). Table 4-7 summarizes pig skin temperature reduction by the two misting approaches (as described in section 3.4.3) applied at the farm prior to the transport period. Supplemental information, including analysis schematics and events considered were introduced in Figure 3-17 in section 3.7.2.

Table 4-7. Summary of skin temperature responses to two different methods of misting prior to transport. Ranges of observations for maximum reduction in skin temperature following the onset of transport, duration of cooling effect, and maximum THI with corresponding duration represent the summary of cooling behavior.

Misting Arrangement	Misting Duration (min)	Maximum ΔT_{skin} (°C)	Time to min T_{skin} (min)	Time to initial T_{skin} (min)	Time to max T_{skin} (min)	Max THI during Transport	Duration of Max THI during Transport
After Loaded (n=6)	5-12	0.8-9.3	7-18	5-11	17-162	83-97	).6 – 23.8%
During Loading (n=5)	20-60	2.2-16	1-12	4-11	4-151	82-96	(33.0 – 63.7%)

Skin temperature reduction (ΔT_{skin}) shown in Table 4-7 represents the best-case scenario of misting efficiency for the two misting approaches. For both methods, the best-case scenario showed potential for cooling, similar durations, and similar consequences for increased THI. The maximum cooling achieved with misting during loading was greater than misting after loading, but the duration of the cooling was similar. From Table 4-7, we can see that misting during loading resulted in much longer duration with THI in the emergency danger zone, which aligns with the expected outcome for adding large amounts of water during hot weather. This indicates that the additional cooling experience with the longer duration of misting may be offset by the potential for increased THI throughout the trip duration. Alternatively, the higher THI may not be at a sufficient level to create a challenge, though no references were found to assess danger levels for THI for pigs during transport.

The cooling observed for the best-case scenario was not realized uniformly throughout the trailer, as observed from the animations, as well as from zone-specific THI distribution. As illustrated by the thermal profile shown in the animations, the cooling effect inside trailer was not uniformly distributed, mostly because the arrangements of misting nozzles varied inside the trailer. Uniform misting effect is important to ensure all pigs get a cooling benefit in hot weather. Uniform distribution of misting nozzles and placement to achieve coverage in all areas of the trailer is required for effectively cooling all pigs. Despite distribution along the length of the trailer, the width of the trailer was not sufficiently covered. Additionally, the form of water application from the nozzles could vary depending on the conditions in which it was applied, mostly based on the water pressure, from fog to droplets.

The animation reveals that cooling from misting during loading lasted longer into the transport period with a greater coverage area inside the trailer as compared to misting after loading. The type of cooling achieved by application of water could vary from air cooling to animal surface cooling. The approaches to optimizing cooling are different for cooling air versus cooling the animal surface and need to be considered when applying water for cooling. For an ideal situation for optimal cooling, intermittent animal surface wetting with steady airflow is recommended inside the trailer to avoid humidity buildup and heat stress. This provides direct cooling to the animal with limited rise in humidity in the air. During loading, there is likely limited airflow through the trailer, so this approach could be difficult to apply. Water application to the animals or bedding directly before leaving the farm could help with animal surface cooling. Another approach in a situation with limited air velocity could be fogging the air inside the trailer to cool the air by evaporative cooling, without directly applying water to the animal surface. This approach results in cooler air temperature but higher relative humidity. This is likely the phenomenon observed in this study, though the characteristics of the misting were not adequately documented to support this hypothesis. This could explain the greater cooling observed for misting while loading as opposed to after loading.

The trailer operator for this study insisted that misting during loading and for the entire duration was a more effective method for cooling the pigs, and the results for best-case scenario for air temperature reduction support that, though the cooling was not observed uniformly throughout the trailer. It is plausible that misting for the longer duration partially compensated for the lack of complete coverage area for misting area within the trailer. It is also plausible that water temperature affects the efficiency of cooling the animals or the air, but it was not recorded in this study. The importance of factors such as water temperature and pressure, as well as effectiveness of each type of cooling, should be further explored.

4.3.4 Effectiveness of Fans with and without Misting in a Stationary Trailer after Transport in Hot Weather

The effectiveness of two cooling methods, including fan operation external to the trailer and external fan operation with misting inside trailer, during the period between transport and unloading with the trailer stopped at the abattoir were evaluated by air temperature, pig skin temperature, and THI observed during the waiting period, as described in section 3.7.2. Trailer thermal responses were characterized by the minimum, average, and maximum zone-centered air temperatures documented for all 6 zones within the trailer during the waiting period, in order to represent the best-case scenario, average-case scenario, and worst-case scenario. The results are summarized in Figures 4-13 through 4-15 and Table 4-8. In addition, trailer internal zone-centered air temperature change was computed for each observation (Table 4-9). Temperature drops and wet-bulb temperature depression for each observation are summarized in Table 4-9, and supplemental time series plots are presented in Figures C-1 through C-12 in Appendix C.

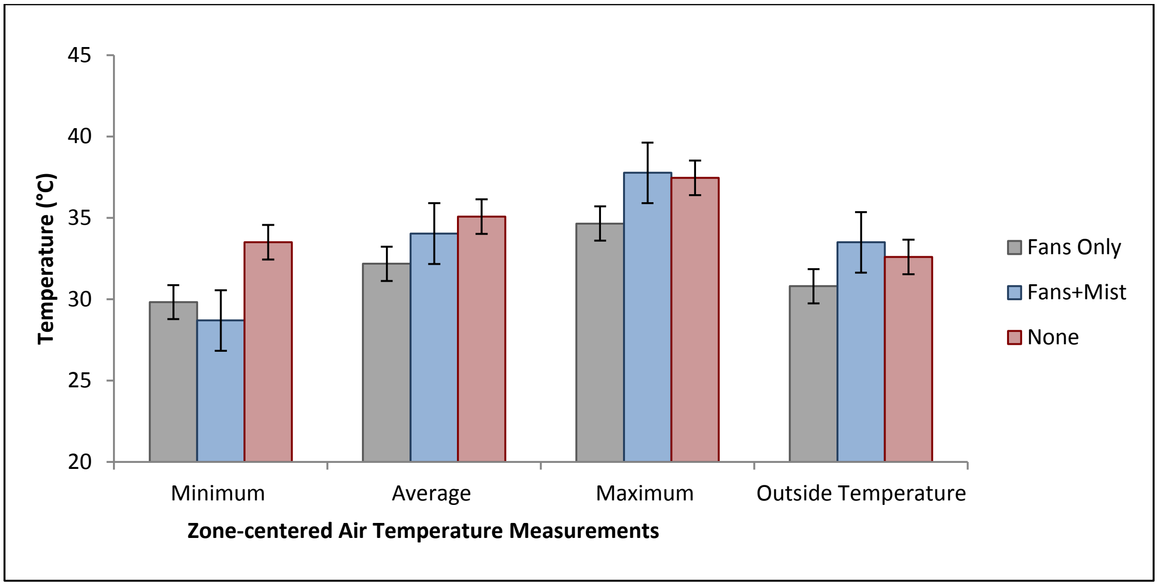

Figure 4-13. Effectiveness of two cooling methods (fan operation external to stationary trailer and fan operation with misting inside the trailer) vs. no cooling, on zone-centered air temperature during hot ambient weather conditions while waiting to unload pigs at the abattoir. Effects are characterized by the minimum, average, and maximum zone-centered air temperature that occurred at any point inside the trailer for each cooling approach. The average outside temperature during the period is included for reference. Supplemental information and characteristics are noted in Table 4-8.

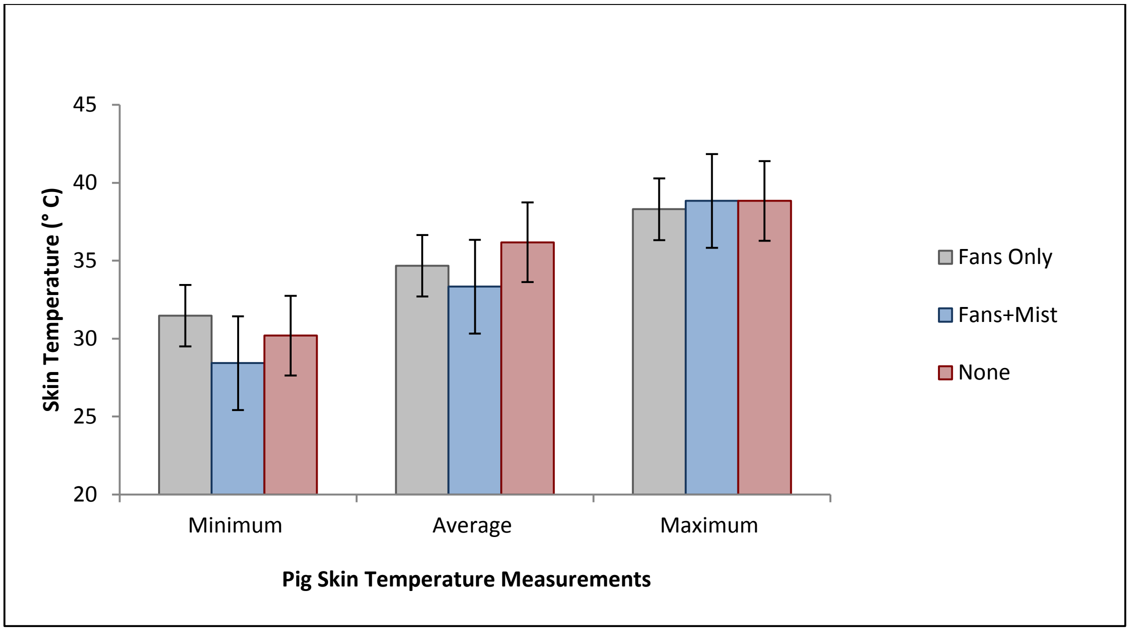

Figure 4-14. Effectiveness of two cooling methods (fan operation external to stationary trailer and fan operation with misting inside the trailer) vs. no cooling, on pig skin temperature during hot ambient weather conditions while waiting to unload pigs at the abattoir. Effects are characterized by the minimum, average, and maximum pig skin temperature that occurred at any point inside the trailer for each cooling approach. Supplemental information and characteristics are noted in Table 4-8.

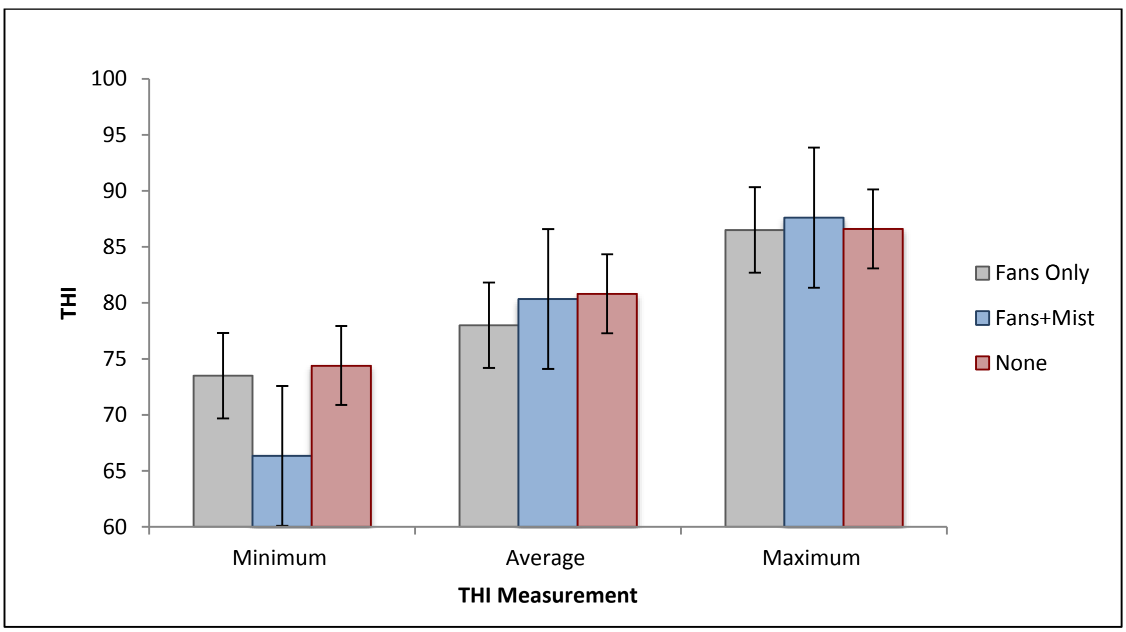

Figure 4-15. Effectiveness of two cooling methods (fan operation external to stationary trailer and fan operation with misting inside the trailer) vs. no cooling, on THI measurements during hot ambient weather conditions while waiting to unload pigs at the abattoir. Effects are characterized by the minimum, average, and maximum THI that occurred at any point inside the trailer for each cooling approach. Supplemental information and characteristics are noted in Table 4-8.

Table 4-8. Characterization of the effects of fans with or without misting or nothing while waiting to unload pigs between transport and unloading while waiting at the abattoir. Data corresponds to Figures 4-13 through 4-15.

Events	Outside Temperature (°C)				Duration (hr)	Number of Observations (n)
	Mean	SD	Min	Max		
Fans only	30.8	4.3	26.0	35.4	0.7 ± 0.2	4
Fans + Misting	33.5	4.9	27.9	37.2	0.4 ± 0.2	3
None	32.6	0.2	27.9	37.2	0.4 ± 0.2	5

Table 4-9. Effectiveness of air cooling within the trailer based on temperature drop for all six zones inside the trailer while waiting at the abattoir between transport and unloading. Corresponds to time-series plots during this period summarized in Appendix C.

Methods	Trip ID	Observation	Temperature Drop (°C)[1]						WBD[2] (°C)
			Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	
None	M2-4[B]	1	-2.1	-3.5	-3.3	0.0	-1.2	-1.4	12.8
	M2-5	2	-0.4	-1.2	-1.7	-0.7	-0.7	-1.5	7.6
	M3-1[A]	3	0.5	*NA*[*]	0.5	0.1	0.4	0.5	11.1
	M3-6	4	*NA*[*]	-0.6	-0.7	-0.2	-0.1	-0.3	13.9
	M3-7	5	*NA*[*]	-1.6	-1.6	-0.8	-0.6	-0.8	13.3
Fans Only	M2-1	1	0.4	0.4	0.7	1.6	2.2	3.6	11.0
	M3-3	2	*NA*[*]	1.5	1.1	-0.5	-0.1	0.2	11.7
	M3-7	3	*NA*[*]	2.0	0.0	-0.1	0.2	-0.1	13.4
	M4-6	4	1.3	0.9	0.9	-0.3	0.4	0.0	4.7
Fans + Mist	M2-1	1	0.8	0.6	0.5	-1.3	-1.4	-3.3	11.3
	M2-4[B]	2	0.6	3.2	3.5	-1.0	0.6	1.3	12.8
	M3-1[A]	3	-1.1	*NA*[*]	-0.6	-0.6	-0.3	-0.7	11.2

[1] For the values in temperature drop column, a positive value indicates to a temperature drop in trailer internal zone-centered air temperature, and a negative value indicates to a temperature rise in trailer internal zone-centered air temperature.
[2] WBD indicates wet-bulb depression.
[*] NA indicates to missing data in corresponding location inside the trailer due to sensor failures.
[A] One down pig documented for this monitoring trip when arrival upon the abattoir.
[B] One dead pig documented in Zone 6 for this monitoring trip when arrival upon the abattoir.

The results presented in this section additionally support the understanding that evaporative cooling is an effective cooling strategy, but it must be applied appropriately to realize the benefit. For each of the zone-centered air temperature measurements, no statistical difference was observed for the three cooling approaches applied (P = 0.31-0.62 for three mean separations). As demonstrated in Figure 4-13, the best-case cooling realized on the trailer was for fans plus misting, while only fans limited the temperature rise but did not cool. On the contrary, the average and worst cases on the trailer did not realize cooling or limits on temperature rise by either fans or fans plus misting. This is further supported by the temperature drop analysis (Table 4-9). A similar trend was observed for pig skin temperature (P = 0.15 - 0.84 for three mean separations) (Figure 4-14). The best-case scenario shows the potential that the responses from all observations were below the skin temperature (35°C) that may cause heat stress of the pigs (Curtis, 1985; Curtis, 1983; DeShazer and Overhults, 1982; Hahn, 1985). The THI analysis (P = 0.10 - 0.94 for three mean separations) (Figure 4-15) did not reveal negative impacts of the misting because even though more moisture was added to the trailer space, the THI did not increase beyond that of no cooling method.

In general, external fans show potential to limit temperature rise inside the trailer, but not every location of the trailer was shown to receive this benefit. Similarly, for application of external fans with misting inside the trailer, cooling effects were observed for some pigs on the trailer, while not much cooling was revealed for the average-case scenario, and no cooling or even a temperature rise for the worst-case scenario. These results somewhat agreed with results reported by Ellis et al. (2008). In their analysis, external fans were running continuously in hot weather while the trailer was waiting to unload the pigs. Air velocity increased and resulted in a 2 to 3°C (3 to 5°F) average compartment air temperature reduction inside the trailer. For the best case scenarios reported in Table 4-9, a similar reduction of 1 to 3°C (2 to 5°F) air temperature reduction is reported. Their study did not clarify if the temperature reduction was observed uniformly throughout the trailer. They also reported that air velocity within the trailer was considerably very low for what might be required to alleviate the temperature and relative humidity in the trailer.

External fan operation with internal misting has the potential to chill some of the pigs despite other pigs simultaneously being heat stressed, which is also supported by the results generated by Ellis et al. (2008). A minimum pig-level air temperature that can chill pigs was observed for pigs that had been exposed in hot trailer zone-centered air temperatures [up to 41°C (106°F), observed] for earlier portions of the trip. Uniform application of fans and misting is essential to prevent or minimize this occurrence.

The observations in this study revealed that fans and misting have potential to alleviate heat stress in a stationary trailer, but the implementation of the methods is critical to realize the benefit in practice. Uniform distribution of misting effect and air velocity within the trailer is important to ensure that all pigs receive benefit from these interventions. Likely, intermittent misting operation or limited misting duration with consistent external fan operation while waiting to unload the pigs at the abattoir could reduce undesirable chilling impact and problematic THI conditions from the unevenly distributed misting effects. The cooling effects of the fan operations and misting may be also influenced by water source temperature, misting pressure, air ventilation, or the exact trailer location from the fan bank. None of these were measured in this study, but are important factors for optimizing the application of countermeasures during hot weather. This study also did not consider the effects of solar radiation on increasing the internal temperature on the trailer, but solar radiation would be an additional heating load and would not be expected to impact the effectiveness of the cooling strategies assessed.

4.4 Assessment of Current TQA Guidelines for Cold Weather Conditions

4.4.1 Zone-specific Skin Temperature Responses for Cold Weather Conditions

The locations of the minimum and maximum pig skin temperature for 22 cool/cold-temperature trips (Figure 4-16) and 4 extreme cold-temperature trips*(Figure 4-17) followed a similar trend to that presented for the overall skin temperature distribution.

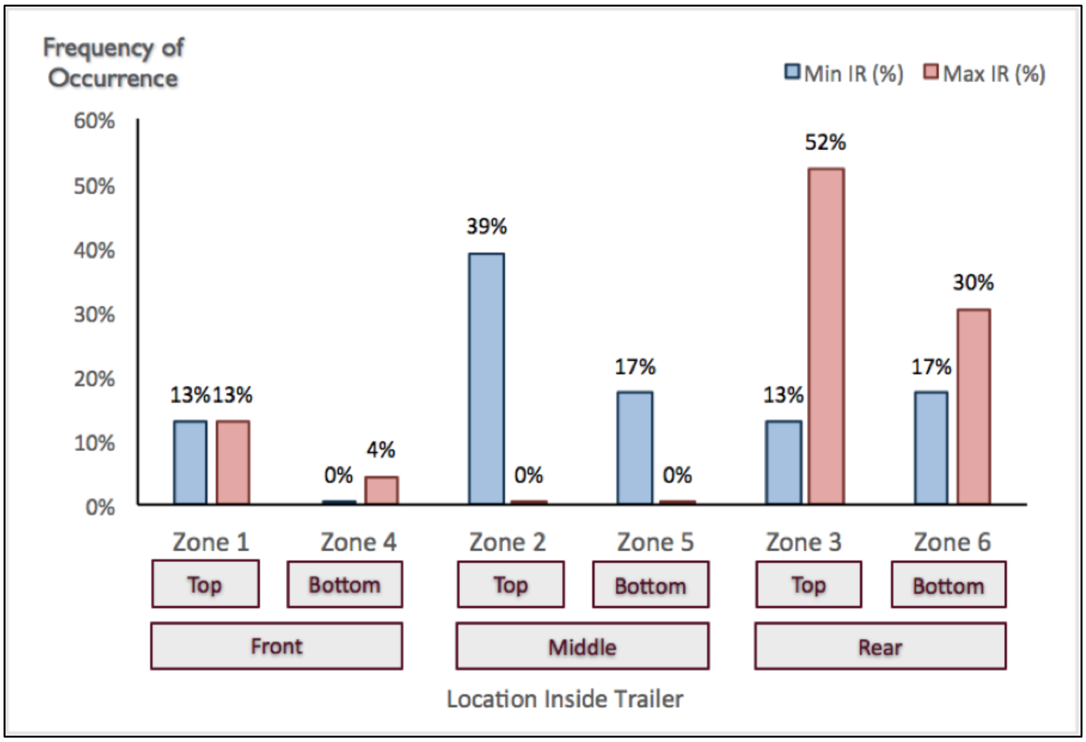

Figure 4-16. Location of maximum and minimum skin temperatures (represented by IR) within the trailer for 22 monitoring trips monitored under cold weather conditions. The rear zones frequently resulted in the warmest skin temperatures on the trailer, and the middle zones frequently resulted in the coolest skin temperatures on the trailer.

* For the outside temperature range < -12°C (10°F), one monitoring trip experienced air temperature sensor failures and was excluded from this analysis.

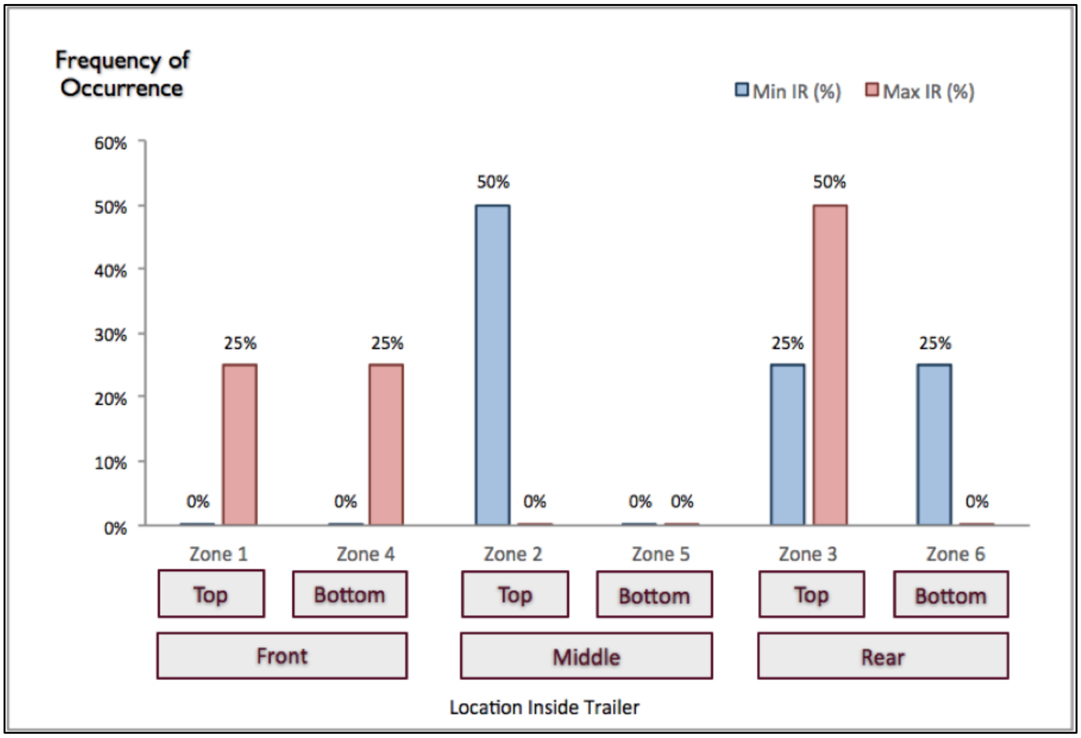

Figure 4-17. Location of maximum and minimum skin temperatures (represented by IR) within the trailer for 4 monitoring trips monitored under extreme cold weather conditions. The occurrences of the maximum skin temperatures are evenly split front and rear, and the occurrences of the minimum skin temperatures evenly split in trailer middle and rear sections.

Minimum skin temperatures were typically located in the center of the trailer. For the 22 cool/cold-temperature trips, 56% of the minimum skin temperatures were observed in the middle sections of the trailer, with 39% and 17% observed in Zone 2 and Zone 5, respectively. The occurrences in the front and rear sections of the trailer were 13% and 30%, respectively. For the 4 extreme cold-temperature trips, 50% of minimum skin temperatures were observed in Zone 2, while 50% of the observations were equally split between Zone 3 and Zone 6 in the rear sections of the trailer.

Maximum skin temperatures were typically located in the rear of the trailer. For the 22 cool/cold-temperature trips, 52% of the maximum pig skin temperatures were observed in Zone 3 and 30% in Zone 6, with the 82% of the total maximum pig skin temperatures occurring in the rear sections of the trailer. The front sections observed 17% of the maximum pig skin temperatures, and there were none in the middle sections of the trailer during these cold-temperature trips. For the 4 extreme cold-temperature trips, 50% of the maximum pig skin temperatures were observed in the rear sections of the trailer, all in the top level Zone 3. The other 50% were observed in the front section, equally split between in Zone 1 and Zone 4. With only 4 trips, there are few observations to consider.

As shown previously in this report, the rear compartments consistently resulted in the warmest skin temperatures on the trailer, and the middle compartments consistently resulted in the coolest skin temperatures on the trailer, regardless of outdoor weather conditions. As indicated in Table 4-5, while only a small portion (0.2 to 10.2% for 70% of the trips evaluated) of duration of transport experienced cold [$-15 < T_{in} < 0$°C ($5 < T_{in} < 32$°F)], the majority of the trailer stayed within cool condition range [0°C < T_{in} < 18°C ($32 < T_{in} < 65$°F)], which may not create a high risk for complications for road transport under 3 hr.

During cold weather conditions, the minimum temperatures in trailer middle sections likely indicate ventilation inlets along the center of the trailer length. Concentrating more trailer boarding in the middle sections may result in shifting some of the ventilation inlets toward the front or rear to create a more uniform temperature distribution inside the trailer and reduce the risk of increasing concentrated cooler temperatures inside the trailer.

4.4.2 Effects of Heavy Bedding on Trailer Thermal Environment

Of all 43 completed monitoring trips, 11 were arranged with heavy bedding (as described in 3.4.2), of which 5 trips were classified as extreme cold temperature trips based on corresponding trailer interior pig-level air temperature. Subzero floor conditions were observed in 8 of the 11 trips. Of the 8 trips that the sub-zero floor temperature occurred, 5 experienced conditions conducive to frozen bedding prior to the loading period, and ice was visually observed on the trailer floor under these conditions. The effects of heavy bedding on trailer thermal environment were classified by the duration of subfreezing floor conditions for three events *(before transport, during transport, and after transport)* with pigs on the trailer.

For the 8 floor-subzero trips evaluated, the distribution of floor temperatures is shown in Figure 4-18, and corresponding supplemental statistics are provided in Table 4-10.

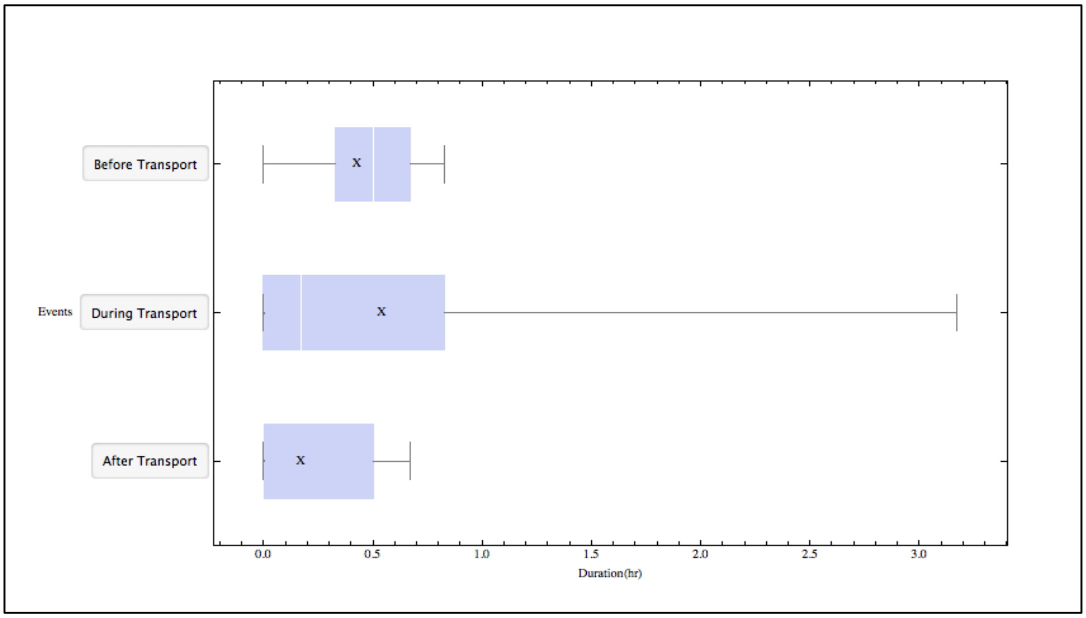

Figure 4-18. Overall distribution of floor temperatures while pigs were on the trailer with heavy bedding, including before transport, during transport, and after transport for 8 trips that were observed under extreme cold conditions.

Table 4-10. Statistical summary of maximum, median, minimum, and average values, and 25% and 75% percentiles of overall duration of floor subfreezing conditions with heavy bedding. Data presented correspond to Figure 4-18.

	Before Transport (hr)	During Transport (hr)	After Transport (hr)
Max	0.8	3.2	0.7
75%	0.7	0.8	0.5
Median	0.5	0.2	0.0
25%	0.3	0.0	0.0
Min	0.0	0.0	0.0
Average	0.4	0.6	0.2

Based solely upon the observed air temperatures in the trailer for the cold conditions, it is not possible to assess the effectiveness of the heavy bedding, though no problems are apparent (Table 4-5). The measurement of floor/bedding temperatures represents another measure of the conditions experienced by the pigs on the trailer (Figure 4-18). The sensors were placed in a rubber casing with slotted openings all around such that the measurement taken was a best representation of the micro-climate near the floor and similar to the expected bedding temperature, which would be influenced by both the air and floor surface. The duration of subzero floor conditions lasted up to 0.8 hr before transport and after transport periods and ranged from 0 to 3.2 hr during transport. Average duration for before transport, during transport and after transport was 0.4 hr, 0.6 hr, and 0.2 hr, respectively.

From this analysis of floor temperatures, the risk of frozen flooring in extremely cold weather was revealed. For all events evaluated, 75% of the subfreezing floor conditions experienced by the pigs were less than 0.8 hr. Dead or down pigs are more prone to occur under more extreme conditions. An extreme occurrence as long as 3.2 hr maximum duration for during transport period was recorded and resulted in the skew observed in the box-and-whisker plot (Figure 4-18). This analysis revealed that some pigs experienced subfreezing floor conditions during the entire transport period under the most extreme weather conditions. For these conditions, heavy bedding may create an adverse environment, with more substrate to hold more moisture and create an ice block on which the pigs ride. Additionally, even with thawed bedding, the capture of moisture in the bedding from urine increases the potential for evaporative cooling, further reducing the temperature within the trailer.

Further exploration of the temperatures (Figure 4-19) focused on the worst-case scenario of floor/bedding conditions experienced by the pigs, which was characterized by maximum duration of floor subfreezing conditions for each trip.

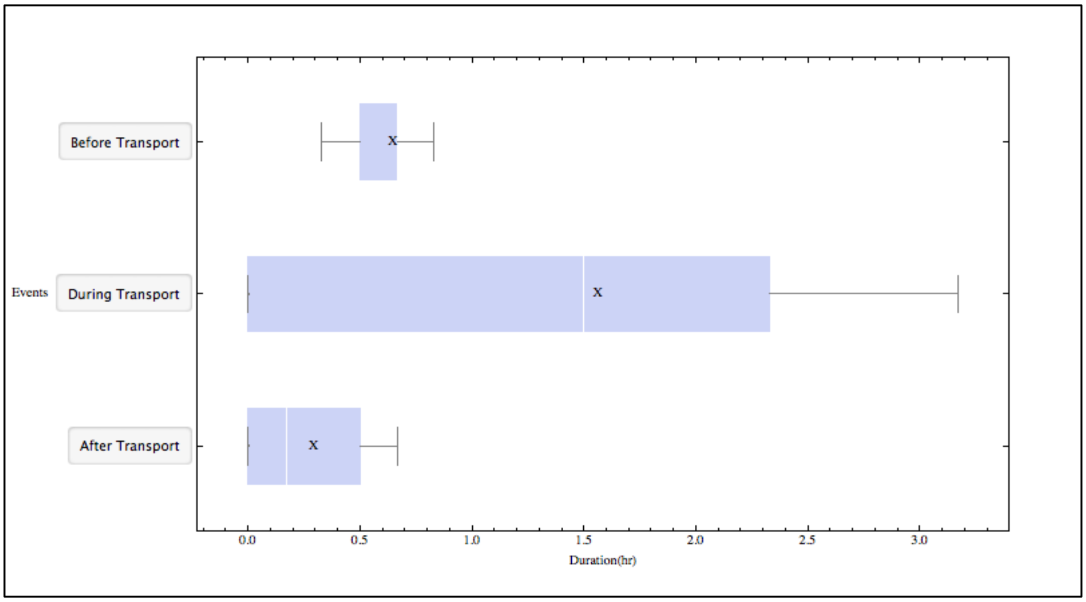

Figure 4-19 Maximum distribution of subzero floor temperatures for the floor sensor on each trip with the longest duration of subfreezing floor temperature in the trailer with heavy bedding, including before transport, during transport and after transport for 8 monitoring trips over extreme cold conditions.

Table 4-11. Summary of maximum, median, minimum, and average values, and 25% and 75% percentiles of the maximum duration of floor subfreezing conditions for the floor sensor on each trip with the longest duration of subfreezing floor conditions with heavy bedding.

	Before Transport (hr)	During Transport (hr)	After Transport (hr)
Max	0.8	3.2	0.7
75%	0.7	2.3	0.5
Median	0.7	1.5	0.2
25%	0.5	0.0	0.0
Min	0.3	0.0	0.0
Average	0.6	1.6	0.3

In terms of the worst-case scenario, the longest duration of subzero floor conditions lasted up to 1.0 hr before transport and after transport periods, and the range stays within 0.3 to 0.8 hr and 0 to 0.7 hr, respectively. The average worst-case scenario for before transport, during transport and after transport was 0.6 hr, 0.6 hr, and 0.3 hr, respectively.

Compared to overall subfreezing floor temperature distributions (Figure 4-18), although the bounds of the floor temperature distributions are similar, the average floor temperatures are higher for before transport and after transport periods, with a more severe worst case observed than the average. For 75% of the trips evaluated, some pigs encountered subfreezing floor conditions for as long as 2.3 hr during the transport period. For the worst-case scenario, the minimum values of the floor subfreezing durations (Figures 4-18 and 4-19) indicating frozen bedding and floor conditions were observed at the start of the transport period and extended for the entire time on the trailer.

Of the 8 monitoring trips in which subfreezing floor and bedding conditions were experienced, 5 trips observed conditions below freezing temperatures which would be conducive to frozen floor and bedding while the trailer was empty between consecutive monitoring trips. This set of conditions would be prone to result in frozen or partially frozen bedding before arriving at the next farm for loading pigs, and moving pigs from a warm barn onto an icy floor would create a significant challenge to thermoregulation. The floor would be expected to remain frozen until the pigs generated enough heat to warm the trailer and thaw the bedding. Figure 4-20 demonstrates the distribution of duration for bedding materials to reach subfreezing condition after the pigs were unloaded at the abattoir for the 5 trips monitored under the coldest outside temperature range (< -12°C).

One approach to avoid this potential condition would be to start every trip with fresh bedding. Under current practices, this is not practical from either a logistics or an economic standpoint. As concerns continue to mount for biosecurity, it may become incentivized for more than thermal reasons.

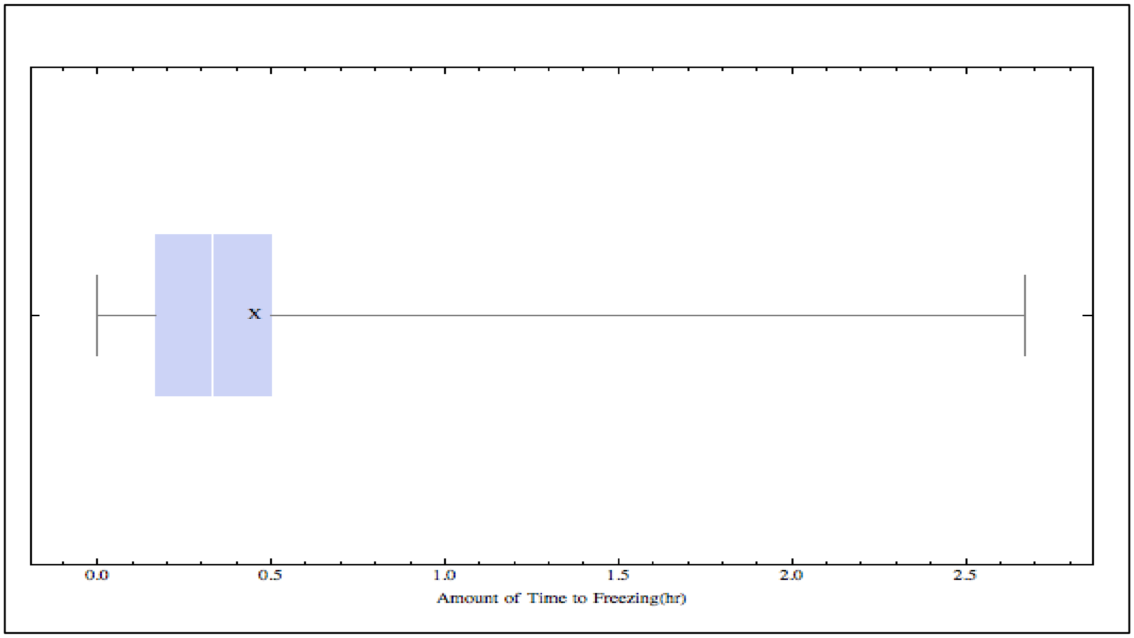

Figure 4-20 Distribution of the amount of time for bedding to reach freezing conditions between unloading and the next loading for 5 monitoring trips over the coldest temperature range.

For 75% of the time, bedding materials cooled to subfreezing conditions in less than 0.5 hr, with a minimum duration of 0 hr, and a maximum duration of 2.7 hr. These results agreed with the maximum duration of subfreezing floor condition analysis, that the pigs experienced icy beddings when they first stepped onto the trailer.

A summary of the times for the trailer floor to reach subfreezing condition between the abattoir and the next farm is included in Table 4-12. The average, minimum, and maximum values of all the floor sensors represent the average-case, best-case and worst-case scenarios. The average case scenario shows that our best estimate for the average time for trailer to reach subfreezing condition is 0.45 hr. By taking the average of the minimum values of the floor sensors, the best estimation for the first sensor in trailer to reach subfreezing condition is 0.1 hr. By averaging the maximum values of all floor sensors, the best prediction of which the last sensor in trailer reaches subfreezing condition is 1.5 hr.

In short, these observations indicate that, on average, a trailer under these conditions will likely have some frozen bedding that the pigs will be loaded onto if the bedding is wet from a previous load and the time between loads is greater than 30 minutes.

Table 4-12 Summary of the length of time for the empty trailer to reach freezing temperatures after pigs were unloaded, including the mean time for all sensors on the trailer to reach freezing, the mean time for the first sensor on the trailer to reach freeze, and the mean time for the last sensor on the trailer to reach subfreezing condition.

Average time for trailer to reach freezing temperature	0.45 (hr)
Time for first sensor in trailer to reach freezing temperature	0.10 (hr)
Time for last sensor in trailer to reach freezing temperature	1.50 (hr)

4.5 Assessment of Alternative Boarding Practices for Cold Weather Conditions

The purpose of exploring alternative boarding strategies was to assess the relative impact of additional boarding on the thermal extremes as well as the viability of altering the ventilation patterns by changing the placement of the boarding.

4.5.1 Comparison of TQA Typical and Alternative Trailer Boarding Arrangements on Pig Skin Temperature

The complete analysis of trailer boarding using pig skin temperature as a response measure (presented in section 4.2.8) is further split into two analyses, one with only TQA typical trailer boarding (31 trips) and one with only alternative trailer boarding variations (12 trips). The results are presented in Figures 4-21 and 4-22. In both Figure 4-21 and 4-22, the maximum and the minimum pig skin temperatures are plotted against the corresponding zone-centered air temperatures and are demonstrated by blocked squares and circles, respectively, and the average is also shown on the figure as a reference.

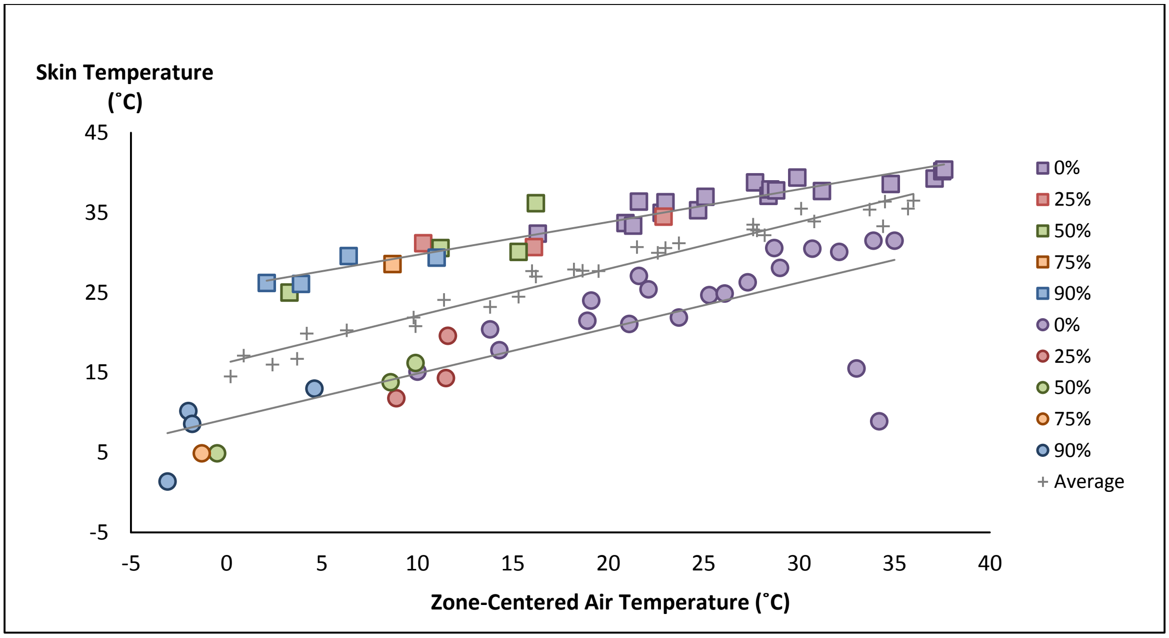

Figure 4-21. Pig skin temperature versus zone-centered air temperature for TQA typical trailer boarding (evenly distributed) for 31 monitoring trips. The maximum skin temperature and the minimum skin temperature are presented by squares and circles. Different TQA typical trailer boarding variations, including 0% to 90% evenly distributed are demonstrated by different colors. The average skin temperature is shown on the figure as a reference.

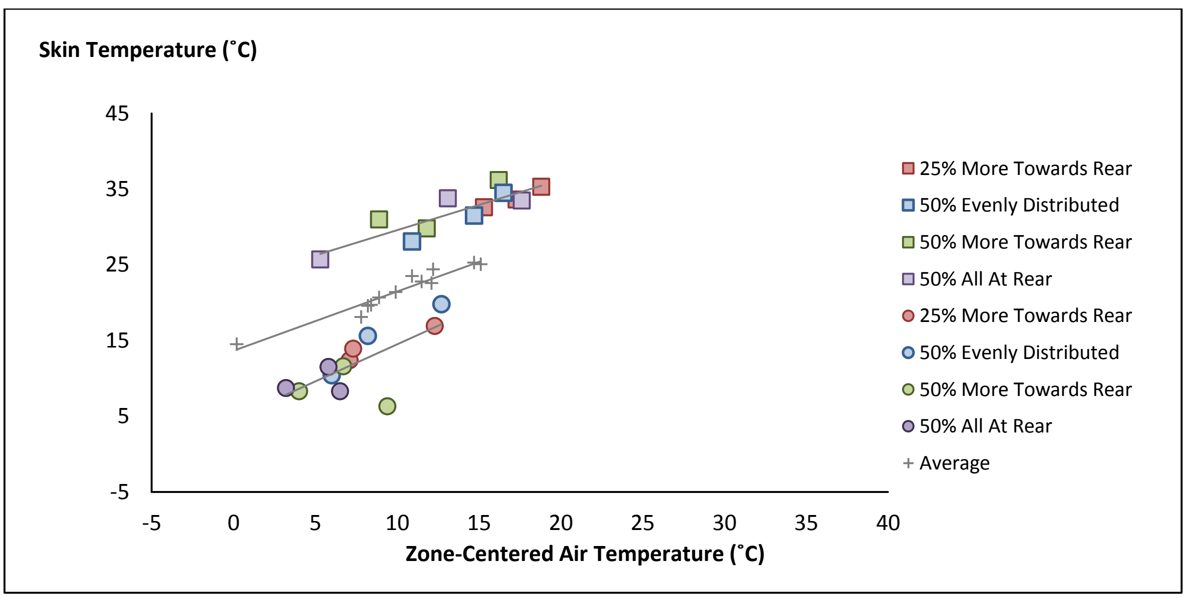

Figure 4-22. Skin temperature versus zone-centered air temperature for alternative trailer boarding variations for 12 monitoring trips. The maximum skin temperature and the minimum skin temperature are presented by squares and circles. Different alternative trailer boarding variations include the percentage of opening covered and distribution of board locations, and vary from the typical application of TQA. The average skin temperature is shown on the figure as a reference.

Figure 4-21 presents responses to TQA assigned trailer boarding variations, including 0%, 25% evenly distributed, 50% evenly distributed, 75% evenly distributed, 90% with bottom covered designate with corresponding outside temperature ranges in TQA guidelines. Figure 4-22 presents three alternative trailer boarding variations, including 25% and 50% distributed more towards rear and 50% placed all at the rear, with percentages corresponding to the TQA guidelines for that outside temperature range, and 50% evenly distributed (as typical for TQA) but within the next cooler outside temperature range (essentially more boarding than the guidelines specify).

No apparent differences can be observed between the responses under TQA typical boarding variations and the alternative boarding variations, with both the maximum and the minimum pig skin temperatures depicting a linear relationship with the corresponding zone-centered air temperature measurements. At the colder temperatures, the minimum skin temperature showed some variability that might be explained by the varying boarding arrangements. Supported by sections 4.2.7 and 4.2.8, the corresponding zone-centered air temperature is a good indicator for corresponding pig skin temperature measurement in the same location within the trailer. Compared to variable boarding percentages and boarding management, trailer interior air temperature has more significant influence on pig skin temperature.

4.5.2 Effects of Deviations from TQA Boarding Practices on Trailer Thermal Environment

The effects of alternative boarding practices on trailer thermal environment are characterized by assessing thermal environment with: (1) the same boarding percentage with altered boarding distributions and (2) additional boarding beyond the recommendation with uniform distribution, using trailer zone-centered air temperature and pig skin temperature responses.

4.5.2.1 *Effects of Boarding Distributed More towards the Rear of the Trailer*

The effects of varying boarding distribution were assessed for three boarding distributions all with 50% boarding, including two trips with evenly distributed boarding, three trips boarding more toward the rear, and three trips boarding all at the rear. Observations were made for outside temperature ranged from -7 to 4°C (20 to 40°F). The results are summarized in Figure 4-23.

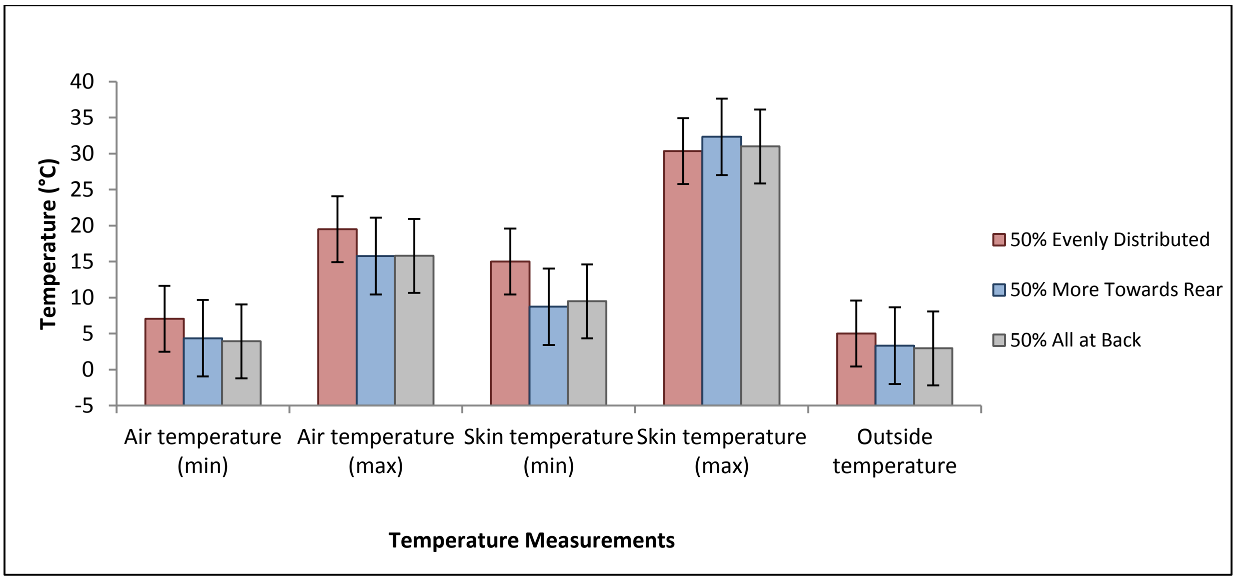

Figure 4-23 Effects of 50% boarding with three different boarding placement arrangements, including evenly distributed (typical TQA implementation, n=2), more towards rear (n=3), and all at rear (n=3). Responses assessed were minimum and maximum zone-centered air temperature measuerements and the minimum and maximum skin temperature . Observations were made under the outside temperature range of -7 to 4°C.

Figure 4-23 shows a trend for more extreme responses for the minimum temperatures with boarding placed more at the rear, though there was no strong statistical difference (P = 0.05-0.82 for four mean separations) between the three boarding distributions evaluated. While not statistically significant, zone-centered air temperatures and the minimum skin temperature for

50% evenly distributed boarding are comparably higher than the other two boarding distributions (Figure 4-23). This supports the possibility that boarding distribution may affect the temperature uniformity, specifically extremes, in the trailer.

The TQA guidelines for boarding with even distribution did not result in notably problematic temperature inside the trailer or for pig skin temperature, but thermal extremes within the trailer were observed. Altering the distribution also did not result in detrimental conditions, though the minimum showed a trend of being cooler than with uniform boarding. Based on this finding, it is plausible that adjusting the boarding did alter the ventilation patterns in the trailer and further concentrated the inlets in one location. When the adjusted distributions were selected, the assumption was that air inlets would be concentrated at the rear of the trailer. Boarding was added at the rear of the trailer to encourage inlets further forward. Results of the animations revealed inlets at the rear was not consistently the case, and it is possible that the boarding at the rear did encourage more inlets toward the front, resulting in even colder temperatures in those areas. This needs further investigation, but should be explored for more boarding toward the front of the trailer.

4.5.2.2 *Effects of Additional Boarding beyond TQA Guidelines*

The addition of boarding beyond the TQA guidelines was explored for effects on zone-centered air temperature measurements and the pig skin temperature for outside temperature ranging from 4 to 9°C. According to TQA, this range should receive 25% trailer boarding. The recommended boarding was compared to boarding at 50%. Maximum and minimum observations for the response variables, representing the best and worst-case scenarios, are summarized in Figure 4-24.

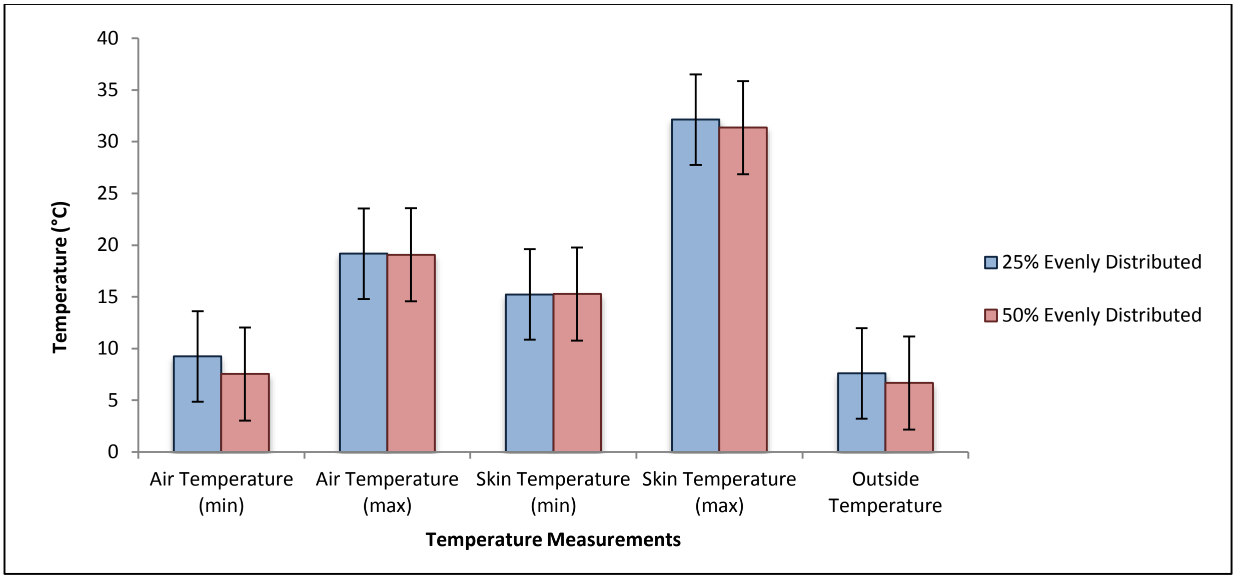

Figure 4-24 Effects of additional boarding beyond TQA guidelines (50% versus 25% for outside temperatures of 4-9°C, n=3) on minimum and maximum zone-centered air temperature and minimum and maximum skin temperatures.

Figure 4-24 shows no statistical difference (P = 0.53 - 0.99 for four mean separations) for zone-centered air temperature or pig skin temperature measurements between the two boarding percentages. By looking at the worst and the best case scenarios, more trailer boarding percentage did not increase the warmest temperature in the trailer, while less boarding percentage did not lower the coldest temperature inside the trailer. This is also supported by the results of frequency of occurrences of thermal conditions that is illustrated in Table 4-5. For outside temperature ranged from -7 to 9°C, the majority of transport internal thermal environment stayed within cool condition [0°C < T_{in} <18°C, (32 < T_{in} <65°F)] and only a small duration of the transport (0.2% to 10.2%) encountered cold condition [-15°C < T_{in} <0°C (5 < T_{in} <32°F)].

Based on these results, the TQA boarding guidelines can safely be modified to allow some additional flexibility and discretion of the trailer operator without compromising the thermal environment of the trailer. The effects of increasing the amount of boarding for other temperature ranges were not fully explored in this study, and the effect of less boarding at the coldest temperatures was also not explored.

CHAPTER 5. SUMMARY AND CONCLUSIONS

5.1 Overall Characteristics of Trailer Thermal Environmental Data

An instrumentation system was designed, constructed and validated for quantifying the thermal environment within a commercial swine trailer during transport. The instrumentation system consisted of six zones in the trailer, each equipped with 14 air temperature sensors in a cross section just above pig level, a central temperature and relative humidity combination sensor for zone-centered thermal environmental profile, an infrared radiometer for pig skin temperature measurements, and temperature sensors in the bedding on the floor. Thermal environment data (temperature at various locations in the trailer to represent a three-dimensional distribution) were collected in the six zones described above over a range of outside temperatures [-14 to 38°C (7 to 100°F]. All sensors were either calibrated or performance checked against manufacturer information before installation onto the trailer.

With trailer management corresponding to TQA guidelines for bedding, boarding, and misting, 43 monitoring trips were completed from May 2012 to February 2013. Of these monitoring trips, 1 trip experienced air temperature sensor failures. The trailer was managed according to TQA guidelines for bedding, boarding, and misting. Placement of the boarding was altered for 12 of the trips to assess the impact of boarding distribution.

The data collected from 43 monitoring trips were used to assess the thermal environment experienced by pigs during all seasonal weather conditions, including cold, mild, and hot weather conditions, with a special focus on extreme hot and cold outside temperature ranges. Specifically, the data were used to assess the occurrences of hot and cold extremes experienced by the pigs on the trailer, general ventilation patterns, and the effectiveness of existing TQA bedding, boarding, and misting recommendations.

The monitoring trips observed road-transport duration ranging from 0.2 hr to 1.5 hr for *before transport* period, 0.8 hr to 4.2 hr for *during transport* period, and 0.1 hr to 1.9 hr for *after transport* period.

For overall thermal conditions analysis, results revealed that for current TQA recommendations, extreme and potentially detrimental thermal conditions were observed within the trailer. Pigs experienced periods of moderate hot thermal conditions [25°C < T_{in} < 35°C (77°F < T_{in} < 95°F)] or moderate cold thermal conditions [-15°C < T_{in} < 18°C (5°F < T_{in} < 64°F)] during transport, and some pigs experienced extreme hot conditions [T_{in} > 35°C (95°F)] or extreme cold conditions [T_{in}<-15°C (5°F)] as the outdoor temperature became more extreme. The duration of the extreme cold events were limited (0.1 to 3.4% of the observations), but the duration of extreme hot events was a larger portion of the trip (19.3 to 68.5% of the observations). Emergency livestock temperature and humidity safety index was observed on the trailer when outside temperature was above 10°C (50°F, 0.1 to 63.7% of observations) despite having much less occurrence of corresponding extreme hot temperature inside the trailer.

For potential ventilation patterns, the hypothesis that the rear of the trailer would be a ventilation inlet and the front would be the exhaust outlet is not supported by the temperature data evaluated. If ventilation inlets were at the rear and exhaust at the front, we would generally expect the warmest conditions to occur at the front of the trailer and the coolest conditions occur at the rear, regardless of outdoor conditions. Temperature distribution patterns generalized in this study did not consistently follow this trend, demonstrating that the ventilation patterns did not follow the same trend for all outdoor conditions and management strategies. Varying boarding levels and distributions show potential for altering the ventilation patters within the trailer, and merits further exploration as a technique to increase thermal uniformity throughout the trailer by manipulating the location of inlets and exhausts.

The zone-specific skin temperature assessment revealed that the rear zones consistently resulted in the warmest pig skin temperatures on the trailer, and the middle zones consistently resulted in the coolest pig skin temperatures on the trailer, regardless of outdoor weather conditions. The same general trend was observed when zone-specific skin temperature was separated out by other weather conditions and boarding percentages. These results further highlight problematic areas within the trailer and the need to achieve more thermal uniformity throughout the trailer.

The floor temperature ranged from -20 to 40°C (-4 to 104°F) prior to the completion of all monitoring trips evaluated, and the minimum floor temperature increased by 5 to 10°C (9 to 18°F) by the end of the transport period. Conditions of sub-freezing floor temperature experienced by the pigs was revealed, evidenced by the extreme cold temperatures observed both during and between trips. This observation raised concern about greater quantities of bedding during the extreme cold weather and the potential for loading pigs onto frozen bedding.

The assessment of trailer bedding depth on skin temperature measurements showed that pig skin temperature was linearly related to the corresponding zone-centered air temperature, and no evidence (based on air, skin, and floor temperatures) was observed to indicate that more bedding provided additional thermal benefits to the pigs.

The overall assessment of trailer boarding variations on pig skin temperature revealed no significant effects on pig skin temperature measurements for the range of trailer boarding percentages. Pig skin temperature was linearly related to the corresponding zone-centered air temperature, regardless of the trailer boarding percentage. Zone-centered air temperature was a good indicator for pig skin temperature, and this general trend was observed when this analysis was broken out by TQA boarding arrangements as well as alternative boarding distributions and percentages.

5.2 Assessment of Current TQA Guidelines for Hot Weather Conditions

The same general trend of the zone-specific skin temperature distribution was observed when the overall zone-specific skin temperature distribution analysis was broken out by warm and hot weather conditions. Analysis of zone-specific THI further reveals that the majority of the maximum THI was observed in Zone 1 and Zone 6 of the trailer. Based on the results of zone-specific skin temperature distribution and zone-specified THI distribution, the rear zones (including Zone 3 and Zone 6) were observed as the potential warmest areas of the trailer with both higher pig skin temperature and higher THI observed throughout the study.

Combined with the temperature distribution analysis, these results support the suggestion that the rear of the trailer was commonly the air outlet.

Observations within the trailer for outside temperature ranging from 10 to 20°C were near pig thermal comfort levels without additional management strategies, such as misting the pigs. We recommend removing the misting recommendation from TQA guidelines for this temperature range because the thermal conditions are acceptable without it, and misting might cool enough to result in chilled pigs.

The cooling effect for misting during loading was very similar to that of misting after loading.

Evidence from the animations contradicted this similarity, with misting while loading yielding a greater reduction in air temperature on the trailer and covering a much greater area of the trailer. The effectiveness of misting is impacted by the location and direction of the misting nozzles such that the coverage area is maximized. Cooling observed in this study was most likely due to the air cooled by "fogging effect" instead of cooling of pigs skin surface. In this observational study, nozzles were arranged to cover the length of the trailer but insufficiently covered the width.

Fans located externally (with or without misting inside) for a stationary trailer stopped at the abattoir prior to unloading, on average, did not show an advantage for cooling the pigs. Cooling was observed for the best-case scenario on the trailer, and would likely be improved by adjusting the placement and operation of the fans and misting nozzles. For example, as illustrated in the animation, the top level of the trailer, where most of the extreme conditions were observed, did not receive the direct flow of the fans in the studied system.

To reduce the risk of the occurrences of chill on hot pigs after a long period of transport duration in hot weather conditions, consistent fan operations with intermittent or limited misting is recommended. The coverage area of both the fans and misting should be uniform throughout the trailer.

5.3 Assessment of Current TQA Guidelines for Cold Weather Conditions

The same general trend of the zone-specific skin temperature distribution was observed when the overall zone-specific skin temperature analysis was separated out by cool and cold weather conditions. For the worst-case scenario, some pigs experienced subfreezing floor conditions during the entire transport period.

Frozen bedding and floor conditions were observed at the start of the transport period for some monitoring trips. Heavy bedding during winter has the potential to increase the quantity of ice and duration of freezing floor conditions.

5.4 Assessment of Alternative Boarding Practices for Cold Weather Conditions

Our data revealed no critical problems with boarding level recommendations based on current TQA guidelines and support the suggestion that boarding guidelines be adjusted to include some flexibility in the boarding amounts and distributions. For outside temperature ranging from -7 to 4°C (19 to 39°F), 50% boarding percentage with evenly distribution resulted in a trend for higher minimum air temperature, pig skin temperature, and maximum air temperature, without encountering problematic thermal conditions based on THI inside the trailer. For outside temperature ranging from 4 to 9°C (19 to 49°F), no difference was observed for both the minimum and the maximum trailer interior air temperature. Our study was limited in the temperature ranges for which boarding level and distribution could be further explored, and the potential impact of further increasing boards at colder temperatures should be considered with respect to maintaining sufficient fresh air and acceptable humidity in the trailer.

5.5 Recommendations for Future Work

The distribution and locations of misting nozzles inside the trailer, and the intensity, intermittency, and locations of fan operation are critical for improving the thermal uniformity of cooling effects throughout the trailer.

Current TQA guidelines do not offer flexibility for drivers to adapt boarding, bedding, and misting guidelines based on responses of pigs, but this could be beneficial in some cases (or at least would not be detrimental). For example, allowing a range of boarding levels with a higher upper limit in temperature range -7 to 20°C (20 to 68°F).

For outside temperature below -7 (20°F) and above 32°C (90°F), the results have shown that pigs experienced extreme thermal conditions inside the trailer with current TQA guidelines, of which the warmest skin temperatures are likely to occur in the rear sections of the trailer while the coolest skin temperatures are experienced in the middle sections of the trailer. This study did not test alternative strategies to alleviate these extremes, but we recommend further exploration into alternative management strategies that could offer improvement.

Based on observations during monitoring trips, stopping for breaks resulted in rapid temperature increases on the trailer [3-4°C (5-7°F) within minutes]. During hot weather, stops should be reduced or extremely limited. During cold weather, stops might provide some relief to the pigs from the freezing conditions, though further implications of this change were not explored in this study.

The cooling effects of the fan operations and misting may be also influenced by water source temperature, misting pressure, air ventilation, or the exact trailer location from the fan bank, which were not measured in this study, but is recommended in future research.

Appendix A. Calibration Data for Sensors in All Monitoring Periods

The linear regression equations for the 84 pig-level air temperature sensors were accomplished by sensor calibration procedure as described in section 3.3.1. The statistics were presented in Table A-1, where CH 1-1 to CH 6-14 identifies the specific pig-level air temperature sensor in corresponding zone location, *linear equation* represents the linear relation between the measured temperature y ($T_{measured}$) and the predicted temperature x (T_{pred}), Reg. *df* indicates the regression degree of freedom, *SE(y|x)* indicates the standard error of $T_{measured}$, and *SE (x|y)* represents the standard error of T_{pred}, *SE (b)* and *SE (a)* represent the standard error of the slope and the standard error or the intercept, respectively, the significance levels of the slope and the intercept were represented by *Sig. (b)* and *Sig. (a)*, and were shown as p-values for each linear equation.

Table A-1 Calibration validation data for pig-level air temperature sensors

Thermistor	Linear Equation	Reg. df	SE (y|x) (°C)	Slope (b)	Sig. (b)	SE (b)	Intercept (a)	SE (a)	Sig. (a)	SE (x|y) (°C)
CH 1-1	y=0.971x + 1.151	14	0.7289	0.971	P < 0.01	0.0106	1.151	0.2438	P < 0.01	0.75071
CH 1-2	y=0.985x + 0.616	14	0.4629	0.985	P < 0.01	0.0067	0.616	0.1548	P < 0.01	0.47010
CH 1-3	y=0.984x + 0.763	14	0.4330	0.984	P < 0.01	0.0063	0.763	0.1448	P < 0.01	0.44016
CH 1-4	y=0.973x + 1.097	14	0.6735	0.973	P < 0.01	0.0098	1.097	0.2253	P < 0.01	0.69210
CH 1-5	y=0.969x + 1.115	14	0.7124	0.969	P < 0.01	0.0104	1.115	0.2383	P < 0.01	0.73493
CH 1-6	y=0.979x + 0.882	14	0.5438	0.979	P < 0.01	0.0079	0.882	0.1819	P < 0.01	0.55527
CH 1-7	y=0.978x + 0.811	14	0.5949	0.978	P < 0.01	0.0087	0.811	0.1990	P < 0.01	0.60814
CH 1-8	y=0.978x + 0.813	14	0.6127	0.978	P < 0.01	0.0089	0.813	0.2049	P < 0.01	0.62622
CH 1-9	y=0.964x + 1.215	14	0.6851	0.964	P < 0.01	0.0100	1.215	0.2291	P < 0.01	0.71043
CH 1-10	y=0.967x + 1.187	14	0.7169	0.967	P < 0.01	0.0104	1.187	0.2398	P < 0.01	0.74135
CH 1-11	y=0.960x + 1.360	14	0.6753	0.960	P < 0.01	0.0098	1.360	0.2259	P < 0.01	0.70332
CH 1-12	y=0.970x + 1.049	14	0.7203	0.970	P < 0.01	0.0105	1.049	0.2409	P < 0.01	0.74276
CH 1-13	y= 0.956 x + 1.528	14	0.7803	0.956	P < 0.01	0.0114	1.528	0.2610	P < 0.01	0.81637
CH 1-14	y=0.969x + 1.109	14	0.7623	0.969	P < 0.01	0.0111	1.109	0.2550	P < 0.01	0.78649
CH 2-1	y= 0.923x + 2.620	14	1.2973	0.923	P < 0.01	0.0189	2.620	0.4339	P < 0.01	1.40507
CH 2-2	y=0.983x + 0.813	14	0.4574	0.983	P < 0.01	0.0067	0.813	0.1530	P < 0.01	0.46532
CH 2-3	y=0.967x + 1.325	14	0.6535	0.967	P < 0.01	0.0095	1.325	0.2186	P < 0.01	0.67578
CH 2-4	y=0.959x+1.574	14	0.7505	0.959	P < 0.01	0.0109	1.574	0.2510	P < 0.01	0.78261
CH 2-5	y=0.960x+1.470	14	0.7831	0.960	P < 0.01	0.0114	1.470	0.2619	P < 0.01	0.81608
CH 2-6	y=0.974x+1.079	14	0.5113	0.974	P < 0.01	0.0074	1.079	0.1710	P < 0.01	0.52492
CH 2-7	y=0.967x+1.225	14	0.6538	0.967	P < 0.01	0.0095	1.255	0.2187	P < 0.01	0.67611
CH 2-8	y=0.964x+1.423	14	0.7584	0.964	P < 0.01	0.0110	1.423	0.2536	P < 0.01	0.78635
CH 2-9	y=0.974x+1.330	14	0.5890	0.974	P < 0.01	0.0086	1.330	0.1970	P < 0.01	0.60481
CH 2-10	y=0.976x+1.134	14	0.6691	0.976	P < 0.01	0.0097	1.134	0.2238	P < 0.01	0.68561
CH 2-11	y=0.971x+1.252	14	0.7725	0.971	P < 0.01	0.0112	1.252	0.2584	P < 0.01	0.79596
CH 2-12	y=0.965x+1.516	14	0.8162	0.965	P < 0.01	0.0119	1.516	0.2730	P < 0.01	0.84600
CH 2-13	y=0.960x+1.599	14	0.7553	0.960	P < 0.01	0.0110	1.599	0.2526	P < 0.01	0.78667
CH 2-14	y=0.972x+1.214	14	0.7025	0.972	P < 0.01	0.0102	1.214	0.2350	P < 0.01	0.72245

Table A-1 (cont.)

CH 3-1	y=0.973x+0.698	14	0.6845	0.973	P < 0.01	0.0100	0.698	0.2289	P < 0.01	0.70337
CH 3-2	y=0.971x+0.815	14	0.6997	0.971	P < 0.01	0.0102	0.815	0.2340	P < 0.01	0.72087
CH 3-3	y=0.979x+0.643	14	0.5759	0.979	P < 0.01	0.0084	0.643	0.1926	P < 0.01	0.58814
CH 3-4	y=0.971x+0.852	14	0.6885	0.971	P < 0.01	0.0100	0.852	0.2303	P < 0.01	0.70938
CH 3-5	y=0.944x+1.632	14	1.1357	0.944	P < 0.01	0.0165	1.632	0.3798	P < 0.01	1.20302
CH 3-6	y=0.968x+0.964	14	0.7115	0.968	P < 0.01	0.0104	0.964	0.2380	P < 0.01	0.73472
CH 3-7	y=0.978x+0.664	14	0.5895	0.978	P < 0.01	0.0086	0.664	0.1972	P < 0.01	0.60290
CH 3-8	y=0.970x+0.967	14	0.6605	0.970	P < 0.01	0.0096	0.967	0.2209	P < 0.01	0.68122
CH 3-9	y=0.972x+0.764	14	0.5836	0.972	P < 0.01	0.0085	0.764	0.1952	P < 0.01	0.60029
CH 3-10	y=0.970x+0.945	14	0.7053	0.970	P < 0.01	0.0103	0.945	0.2359	P < 0.01	0.72738
CH 3-11	y=0.984x+0.565	14	0.4363	0.984	P < 0.01	0.0063	0.565	0.1459	P < 0.01	0.44359
CH 3-12	y=0.971x+0.894	14	0.6679	0.971	P < 0.01	0.0097	0.894	0.2234	P < 0.01	0.68816
CH 3-13	y=0.969x+0.931	14	0.7183	0.969	P < 0.01	0.0105	0.931	0.2402	P < 0.01	0.74106
CH 3-14	y=0.964x+1.070	14	0.7726	0.964	P < 0.01	0.0112	1.070	0.2584	P < 0.01	0.80110
CH 4-1	y=0.951x+1.764	14	0.8843	0.951	P < 0.01	0.0129	1.764	0.2958	P < 0.01	0.92954
CH 4-2	y=0.950x+1.738	14	0.8768	0.950	P < 0.01	0.0128	1.738	0.2933	P < 0.01	0.92337
CH 4-3	y=0.969x+1.194	14	0.6490	0.969	P < 0.01	0.0094	1.194	0.2171	P < 0.01	0.66963
CH 4-4	y=0.952x+1.675	14	0.8875	0.952	P < 0.01	0.0129	1.675	0.2968	P < 0.01	0.93191
CH 4-5	y=0.953x+1.573	14	0.8848	0.953	P < 0.01	0.0129	1.573	0.2959	P < 0.01	0.92862
CH 4-6	y=0.952x+1.755	14	0.8966	0.952	P < 0.01	0.0130	1.755	0.2999	P < 0.01	0.94168
CH 4-7	y=0.964x+1.321	14	0.7495	0.964	P < 0.01	0.0109	1.321	0.2507	P < 0.01	0.77781
CH 4-8	y=0.949x+1.867	14	0.9068	0.949	P < 0.01	0.0132	1.867	0.3033	P < 0.01	0.95595
CH 4-9	y=0.960x+1.478	14	0.7306	0.960	P < 0.01	0.0106	1.478	0.2443	P < 0.01	0.76128
CH 4-10	y=0.954x+1.629	14	0.8023	0.954	P < 0.01	0.0117	1.629	0.2683	P < 0.01	0.84090
CH 4-11	y=0.962x+1.463	14	0.7295	0.962	P < 0.01	0.0106	1.463	0.2440	P < 0.01	0.75856
CH 4-12	y=0.954x+1.668	14	0.8394	0.954	P < 0.01	0.0122	1.668	0.2807	P < 0.01	0.87948
CH 4-13	y=0.956x+1.659	14	0.7933	0.956	P < 0.01	0.0115	1.659	0.2653	P < 0.01	0.82978
CH 4-14	y=0.953x+1.747	14	0.8106	0.953	P < 0.01	0.0118	1.747	0.2711	P < 0.01	0.85059

Table A-1 (cont.)

CH 5-1	y=0.976x+0.686	14	0.6588	0.976	P < 0.01	0.0096	0.686	0.2203	P < 0.01	0.67513
CH 5-2	y=0.955x+1.280	14	0.9120	0.955	P < 0.01	0.0133	1.280	0.3050	P < 0.01	0.95490
CH 5-3	y=0.972x+0.787	14	0.6493	0.972	P < 0.01	0.0094	0.787	0.2171	P < 0.01	0.66801
CH 5-4	y=0.918x+2.386	14	1.4542	0.918	P < 0.01	0.0212	2.386	0.4864	P < 0.01	1.58437
CH 5-5	y=0.962x+1.136	14	0.8538	0.962	P < 0.01	0.0124	1.136	0.2856	P < 0.01	0.88782
CH 5-6	y=0.971x+0.874	14	0.6633	0.971	P < 0.01	0.0097	0.874	0.2219	P < 0.01	0.68339
CH 5-7	y=0.955x+1.221	14	0.9802	0.955	P < 0.01	0.0143	1.221	0.3279	P < 0.01	1.02675
CH 5-8	y=0.963x+0.954	14	0.8016	0.963	P < 0.01	0.0117	0.954	0.2681	P < 0.01	0.83210
CH 5-9	y=0.966x+0.848	14	0.6849	0.966	P < 0.01	0.0100	0.848	0.2291	P < 0.01	0.70877
CH 5-10	y=0.966x+0.924	14	0.6389	0.966	P < 0.01	0.0093	0.924	0.2137	P < 0.01	0.66144
CH 5-11	y=0.963x+1.088	14	0.7160	0.963	P < 0.01	0.0104	1.088	0.2395	P < 0.01	0.74344
CH 5-12	y=0.963x+1.054	14	0.6064	0.963	P < 0.01	0.0088	1.054	0.2028	P < 0.01	0.62950
CH 5-13	y=0.961x+0.945	14	0.7995	0.961	P < 0.01	0.0116	0.945	0.2674	P < 0.01	0.83176
CH 5-14	y=0.961x+1.114	14	0.8235	0.961	P < 0.01	0.0120	1.114	0.2754	P < 0.01	0.85670
CH 6-1	y=0.971x+0.786	14	0.6526	0.971	P < 0.01	0.0095	0.786	0.2183	P < 0.01	0.67236
CH 6-2	y=0.960x+1.068	14	0.8826	0.960	P < 0.01	0.0128	1.068	0.2952	P < 0.01	0.91941
CH 6-3	y=0.961x+1.031	14	0.8326	0.961	P < 0.01	0.0121	1.031	0.2785	P < 0.01	0.86683
CH 6-4	y=0.962x+1.161	14	0.7888	0.962	P < 0.01	0.0115	1.161	0.2638	P < 0.01	0.82014
CH 6-5	y=0.967x+0.875	14	0.7836	0.967	P < 0.01	0.0114	0.875	0.2621	P < 0.01	0.81022
CH 6-6	y=0.957x+1.107	14	0.9202	0.957	P < 0.01	0.0134	1.107	0.3078	P < 0.01	0.96200
CH 6-7	y=0.966x+0.974	14	0.7355	0.966	P < 0.01	0.0107	0.974	0.2460	P < 0.01	0.76145
CH 6-8	y=0.957x+1.253	14	0.7705	0.957	P < 0.01	0.0112	1.253	0.2577	P < 0.01	0.80554
CH 6-9	y=0.961x+1.117	14	0.8792	0.961	P < 0.01	0.0128	1.117	0.2941	P < 0.01	0.91525
CH 6-10	y=0.951x+1.355	14	0.8671	0.951	P < 0.01	0.0126	1.355	0.2900	P < 0.01	0.91207
CH 6-11	y=0.962x+1.036	14	0.8791	0.962	P < 0.01	0.0128	1.036	0.2940	P < 0.01	0.91419
CH 6-12	y=0.946x+1.528	14	1.1249	0.946	P < 0.01	0.0164	1.528	0.3762	P < 0.01	1.18887
CH 6-13	y=0.962x+1.054	14	0.7772	0.962	P < 0.01	0.0113	1.054	0.2599	P < 0.01	0.80762
CH 6-14	y=0.963x+0.957	14	0.8833	0.963	P < 0.01	0.0129	0.957	0.2954	P < 0.01	0.91702

Appendix B. External Environment Sensor Calibration

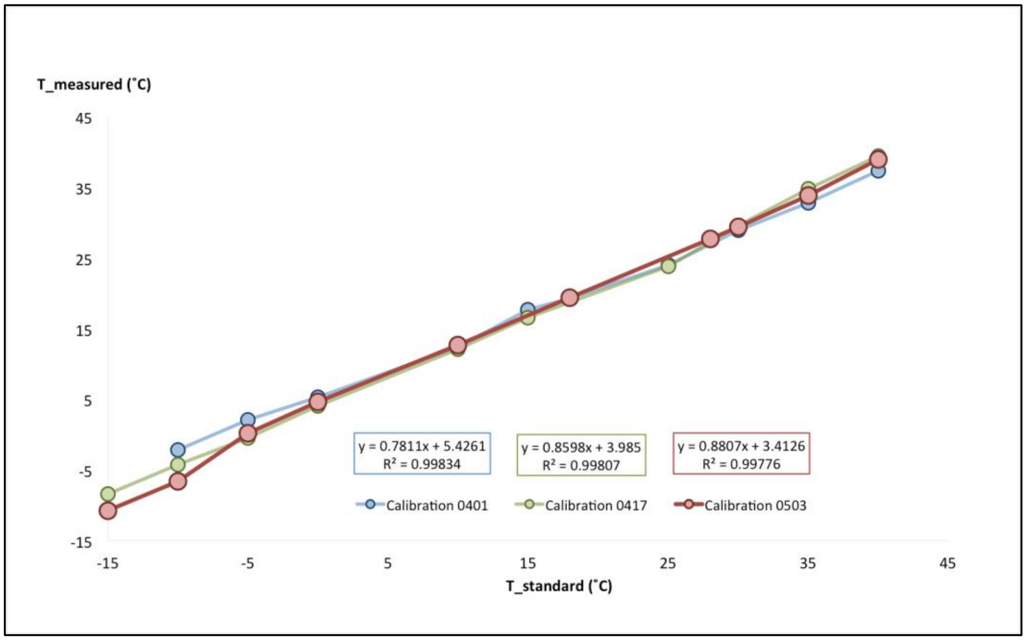

Figure B-1. Three replications of the external environment sensor calibration curves over a temperature range from -15°C to 40°C against an NIST certified block temperature calibrator.

Figure B-1 shows three calibration curves and linearly regressed equations of the calibrations conducted for the external environment sensor (S-THB-M008) over the temperature range from -15°C to 40°C, with three replications on different dates, accordingly. The x-axis corresponds to the standard temperature derived from the NIST certified block temperature calibrator (CL-134, OMEGA) and y-axis corresponds to the external environment sensor temperature measurements regarding to the standard temperature set points.

A statistics summary table (Table B-1) for external environment sensor derived from the three calibrations is listed below. Se indicates the standard error, Se (b) indicates the standard error of the intercepts, Se (a) indicates the standard error of the slope and $Se_{(pred)}$ indicates the standard uncertainty of the according calibrations, respectively.

Table B-1. Statistics Summary for External Environment Sensor Calibrations.

Calibrations	Se (°C)	Intercept (b) (°C)	X variable (a)	Se (b) (°C)	Se(a) (°C)	$Se_{(pred)}$(°C)
Calibration_ 0401	0.61	5.28	0.78	0.25	0.01	0.78
Calibration_0417	0.74	3.99	0.86	0.28	0.01	0.86
Calibration_0503	0.88	3.41	0.88	0.33	0.01	1.00

The calibration curves illustrated in Figure B-1 demonstrate that as standard temperature increases according to the calibration temperature range, the measured temperature of external environment sensor increases with the same trend, and all three calibration curves (Calibration 0401, Calibration 0417 and Calibration 0503) show a linear regression between the standard temperature ($T_{\_standard}$) and measured temperature ($T_{\_measured}$). However, as the standard temperature decreases from an elevated temperature (40° C) to a temperature that was below 0° C, the external environment temperature sensor failed to represent appropriate temperatures. From Table B-1, the according x variables for each calibration were 0.78, 0.86 and 0.88, and the standard uncertainties were 0.78°C, 0.86°C and 1.00°C, which illustrate an unstable sensor performance.

Appendix C. Supplemental Analyses of Current TQA Industry Practices for Hot Weather Conditions

For each of the distinguish observation implemented with the corresponding cooling strategy that were described in 3.7.2, trailer zone-centered air temperature in each of the six zones within the trailer and the outside temperature were plotted against the elapsed time during the waiting period prior to unload the pigs when the trailer was stopped at the abattoir. The results are shown in Figure C-1 to Figure C-12.

C.1 Effects of Fan Operation Only on Thermal Environment in a Stationary Trailer before Unloading at Abattoir

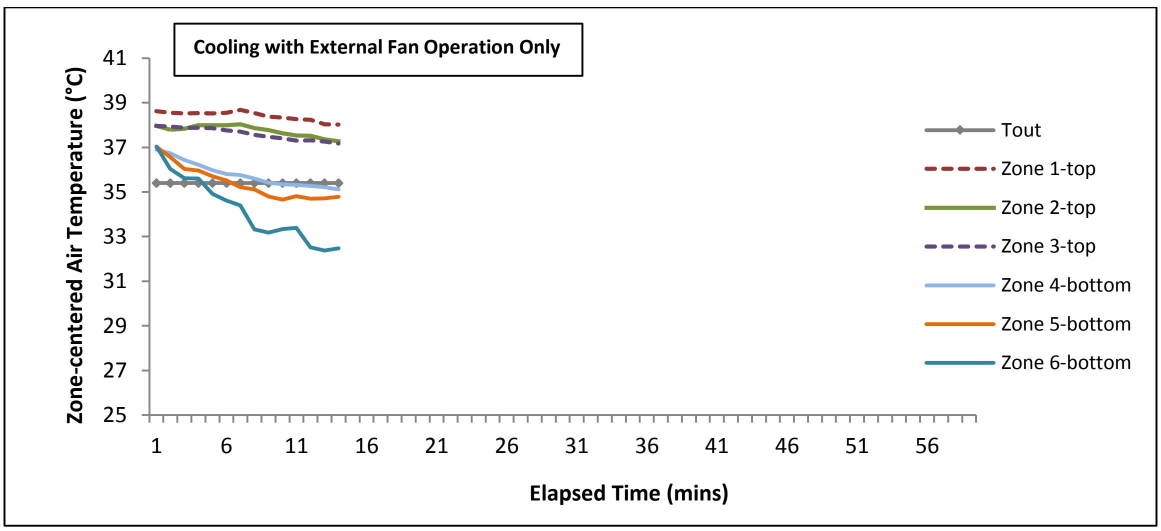

Figure C-1. Trailer interior zone-centered air temperature and outside temperature change with fan operation external to stationary trailer only during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the first of four distinguish observations encountered with this cooling method at the abattoir.

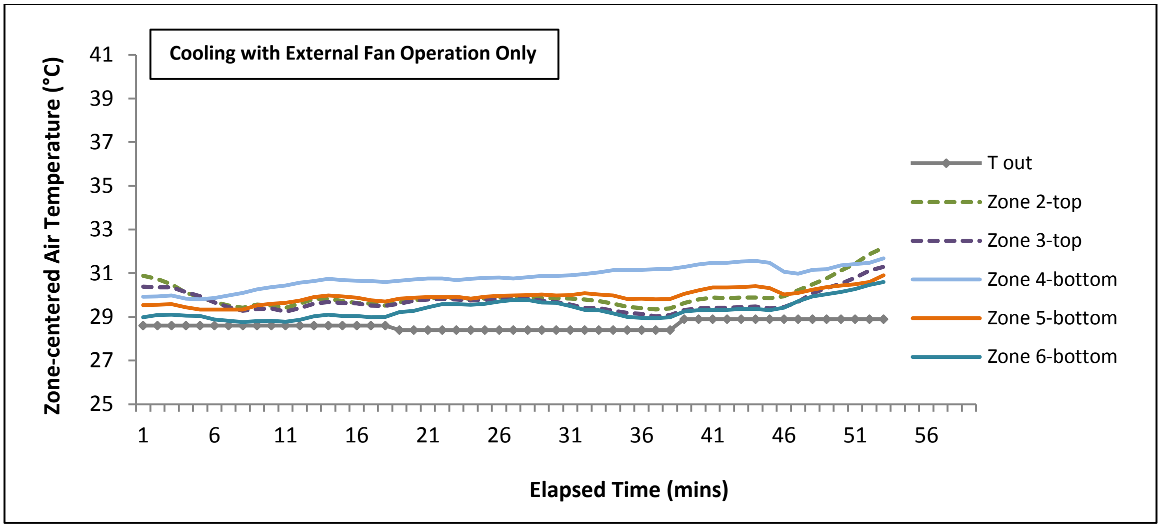

Figure C-2. Trailer interior zone-centered air temperature and outside temperature change with fan operation external to stationary trailer only during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the second of four distinguish observations encountered with this cooling method at the abattoir.

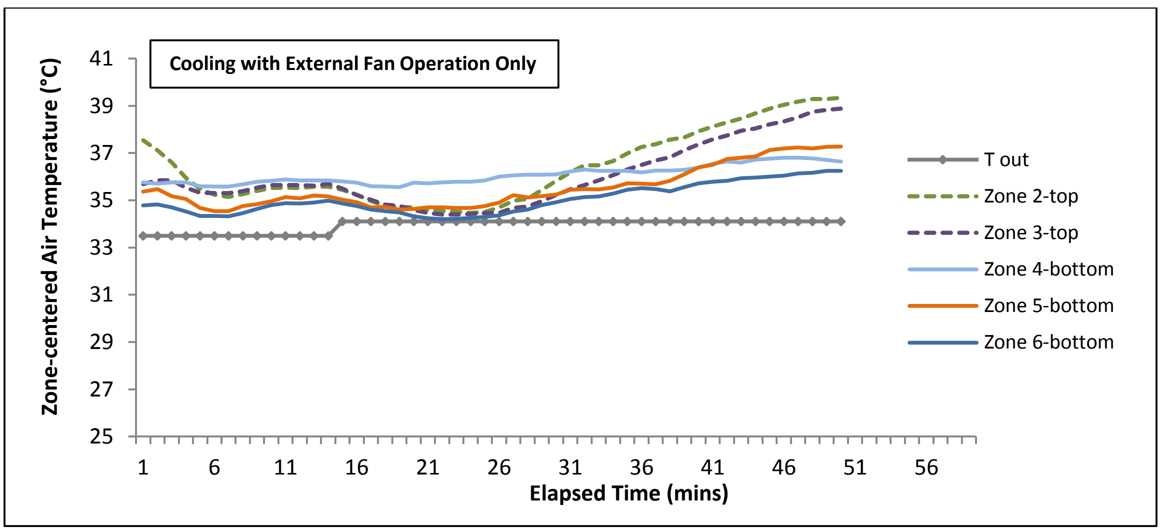

Figure C-3. Trailer interior zone-centered air temperature and outside temperature change with fan operation external to stationary trailer only during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the third of four distinguish observations encountered with this cooling method at the abattoir.

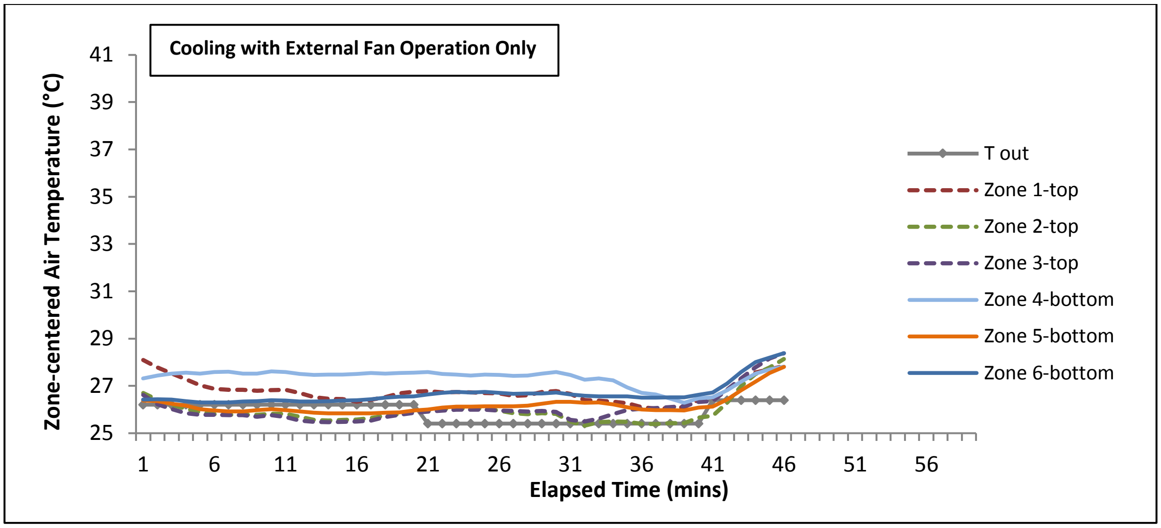

Figure C-4.Trailer interior zone-centered air temperature and outside temperature change with fan operation external to stationary trailer only during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the fourth of four distinguish observations encountered with this cooling method at the abattoir.

C.2 Effects of Fan and Misting on Thermal Environment in a Stationary Trailer before Unloading at Abattoir

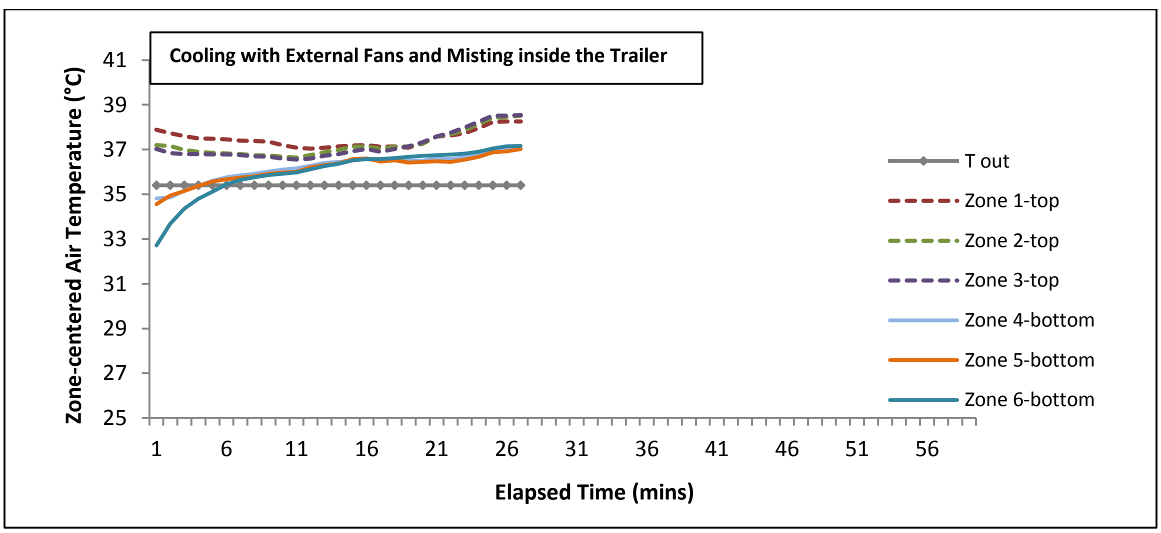

Figure C-5. Trailer interior zone-centered air temperature and outside temperature change with external fan operation with misting inside a stationary trailer during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the first of three distinguish observations encountered with this cooling method at the abattoir.

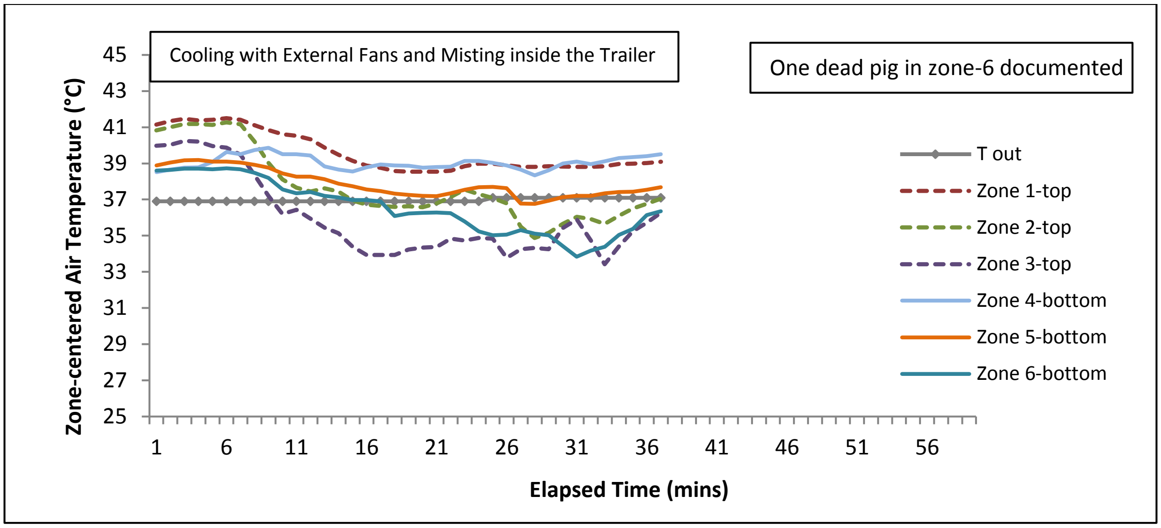

Figure C-6. Trailer interior zone-centered air temperature and outside temperature change with external fan operation with misting inside a stationary trailer during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the second of three distinguish observations encountered with this cooling method at the abattoir.

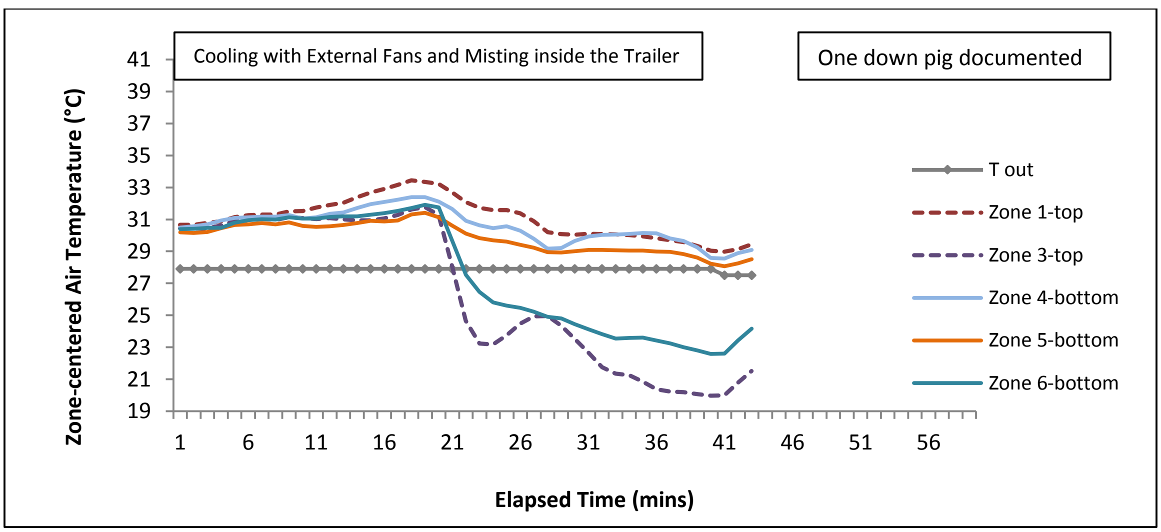

Figure C-7 Trailer interior zone-centered air temperature and outside temperature change with external fan operation with misting inside a stationary trailer during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the third of three distinguish observations encountered with this cooling method at the abattoir.

C.3 Effects of No Cooling Method on Thermal Environment in a Stationary Trailer before Unloading at Abattoir

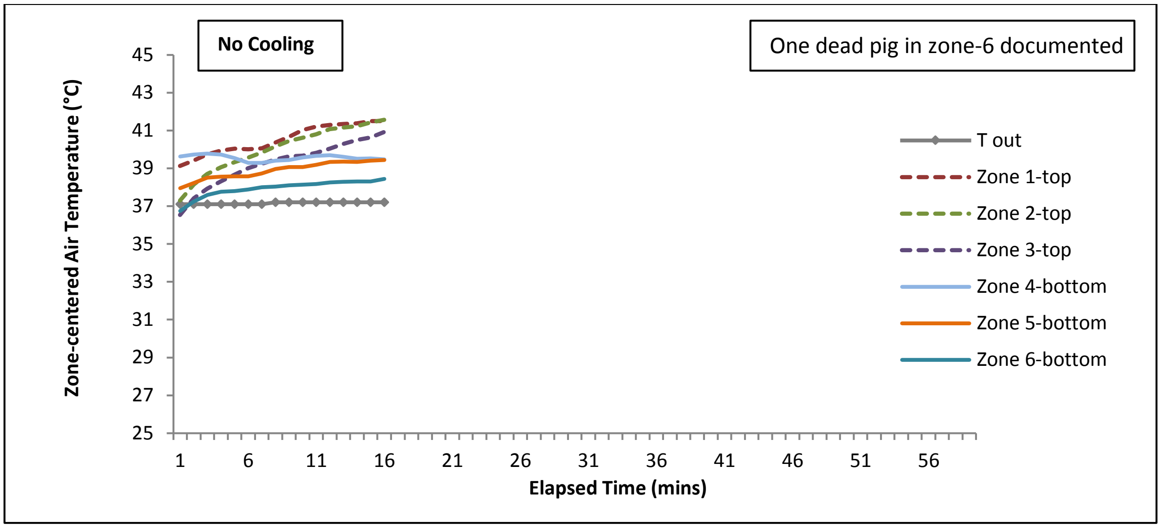

Figure C-8. Trailer interior zone-centered air temperature and outside temperature change with no cooling strategy during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the first of five distinguish observations encountered with this cooling method at the abattoir.

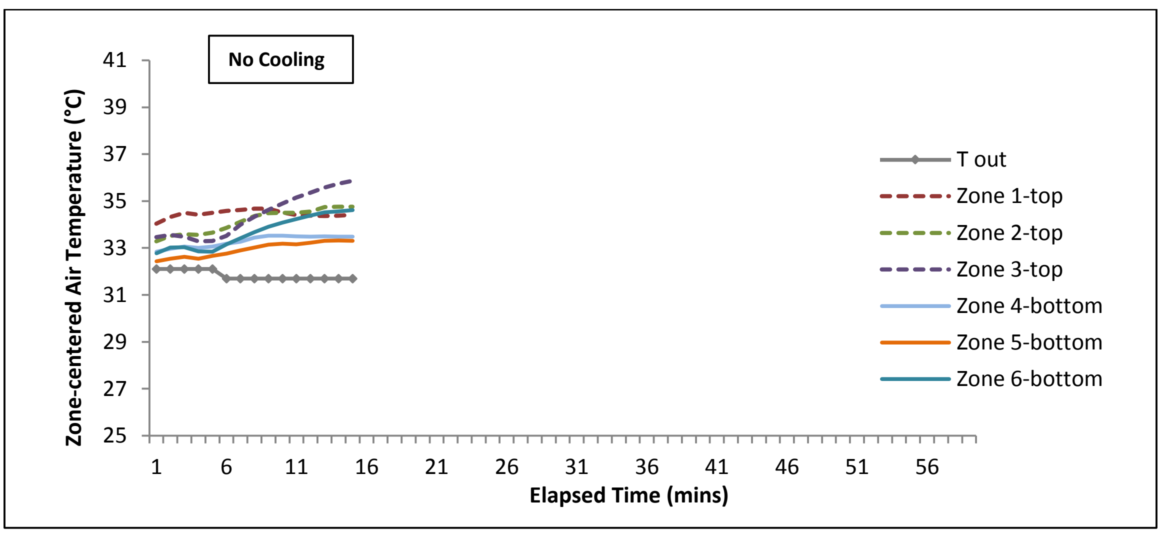

Figure C-9. Trailer interior zone-centered air temperature and outside temperature change with no cooling strategy during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the second of five distinguish observations encountered with this cooling method at the abattoir.

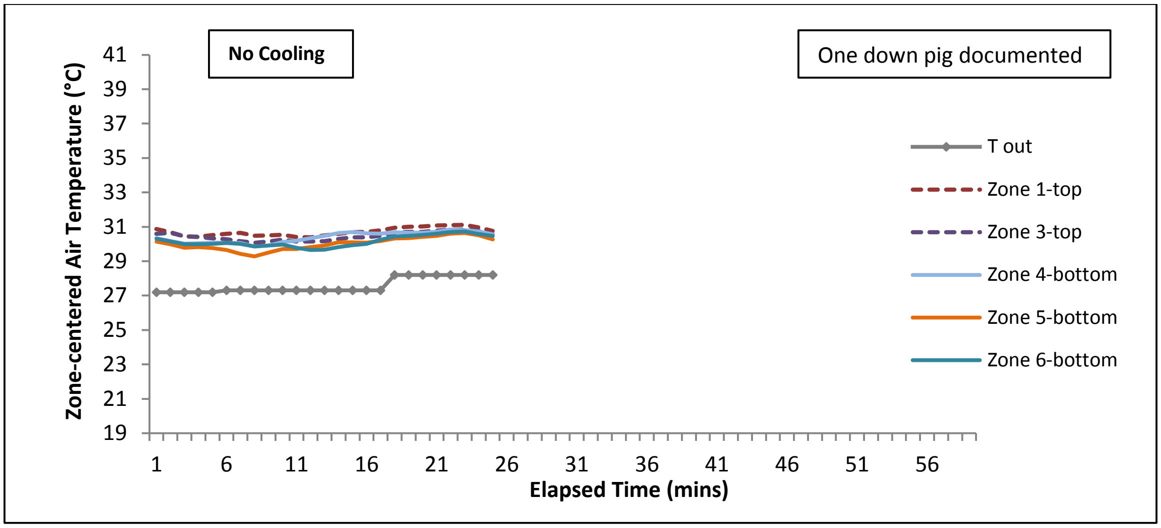

Figure C-10. Trailer interior zone-centered air temperature and outside temperature change with no cooling strategy during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the third of five distinguish observations encountered with this cooling method at the abattoir.

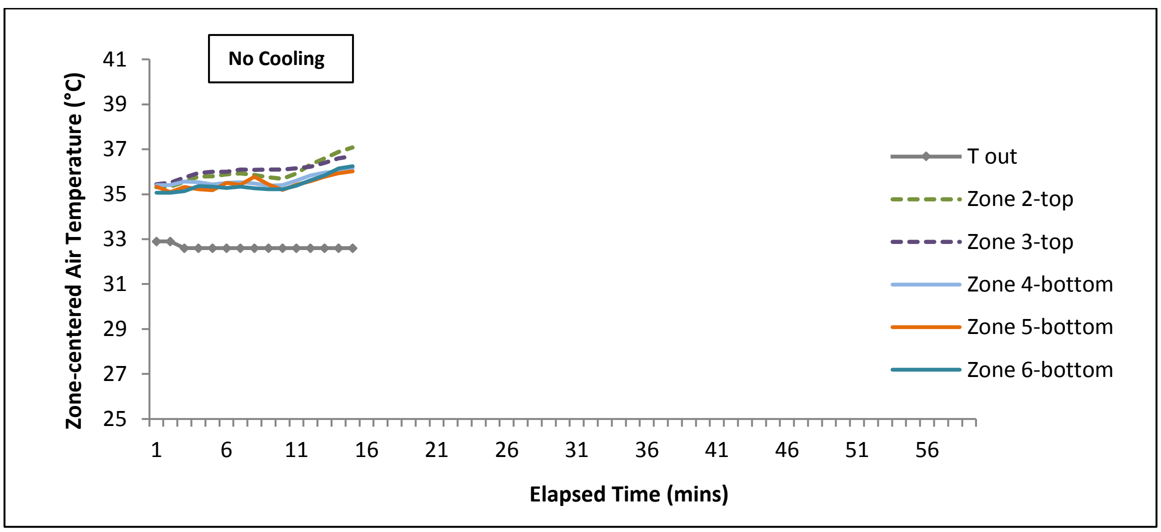

Figure C-11. Trailer interior zone-centered air temperature and outside temperature change with no cooling strategy during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the fourth of five distinguish observations encountered with this cooling method at the abattoir.

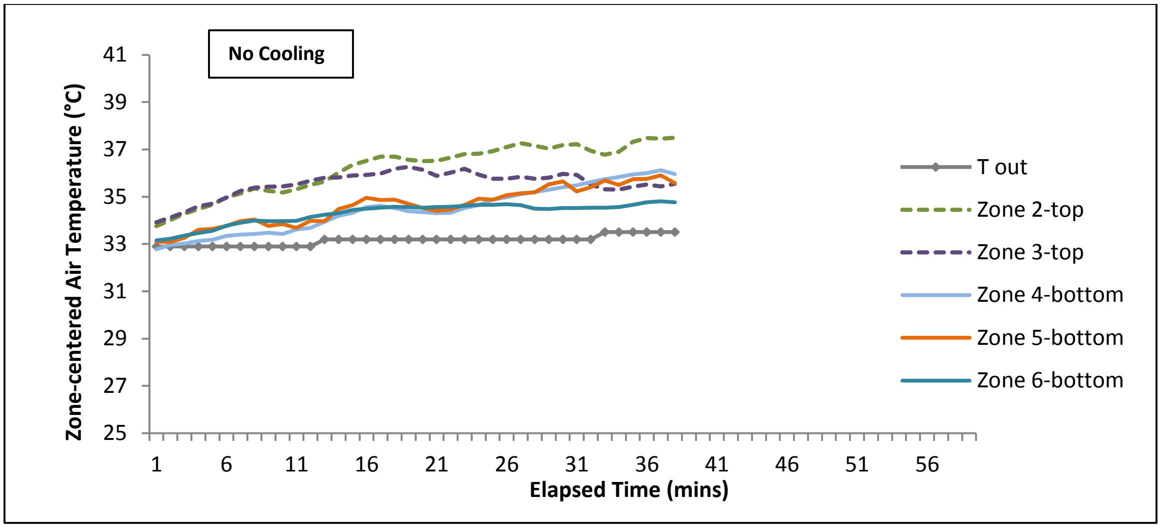

Figure C-12. Trailer interior zone-centered air temperature and outside temperature change with no cooling strategy during hot ambient weather conditions while waiting to unload pigs at the abattoir. This figure represents the fifth of five distinguish observations encountered with this cooling method at the abattoir.

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