Title: Establishing Bedding and Boarding Requirements for Finisher Pigs Through Scientific Validation – Micro-study – **NPB #10-175**

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Industry Summary

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 and down pigs following transport. 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 along 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 and a surface IR thermometer were installed on the central ceiling of each zone to measure a representative moist-air state point for each compartment and the temperature of the pigs' backs. 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 the commercial hauler and corresponding to the National Pork Board Transport Quality Assurance (TQA) guidelines (NPB, 2008). 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 encountered (7 to 100 °F; -14 to 38°C).

Results showed that for outside temperature below 20°F (-7°C) and above 90°F (32°C), pigs experienced extreme thermal conditions inside the trailer with current TQA guidelines. For many scenarios with extreme conditions observed, the worst-case scenario could have been improved with greater uniformity in trailer ventilation and/or application of cooling method.

The ventilation patterns inside the trailer did not follow the same trend for all monitoring trips, revealing potential to manipulate ventilation patterns with trailer management strategies. This approach for improving the thermal extremes needs further exploration, but may offer a strategy to avoid the most extreme cold microclimates within the trailer.

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, resulting in limited benefit observed for these methods in this study. When outside temperature ranged from 50 to 69°F (10 to 20°C), trailer environment was within acceptable thermal limits without misting the pigs, demonstrating no need for this recommendation in TQA.

During cold weather, frozen floor conditions were observed, with floor temperature as cold as -4 °F (-20°C) in some areas of the trailer. No evidence indicated that bedding depth had a measurable effect on the thermal comfort of the pigs, and 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 within the less extreme outdoor temperatures.

Additionally, observations revealed rapid temperature increases when the trailer came to a stop for several minutes. The study also revealed the need for development of a weather safety index appropriate for pigs which could be applied to pigs during transport.

More detailed discussion over this summary and potential changes to the current TQA guidelines is included near the end of this report.

Abstract

Forty-three monitoring trips were completed to assess the thermal micro-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 collected 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.

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 7 to 100 °F (-14 to 38 °C). With trailer management corresponding to TQA guidelines for bedding, boarding, and misting, 43 monitoring trips were completed from May 2012 to February 2013. The trailer was managed by the cooperating driver 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 monitoring trips observed road-transport duration ranging from 0.2 h to 1.5 h for before transport period, 0.8 h to 4.2 h for during transport period, and 0.1 h to 1.9 h for after transport period.

Results revealed that for current TQA recommendations, extreme and potentially detrimental thermal conditions were observed within the trailer for outside temperature below20°F (-7°C) and above 90°F (32°C). The duration of the extreme cold events were limited (0.1 to 3.4% of the observations during trips observing Tin<5°F (-15°C), but the extreme hot was a larger portion of the trip (19.3 to 68.5% of the observations during trips observing Tin>95°F (35°C)). Emergency Livestock Weather Safety Index was

observed on the trailer when outside temperature was above 50°F (10°C) (0.1 to 63.7% of observations with Emergency conditions) despite having much less occurrence of corresponding extreme hot temperature inside the trailer.

The 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 skin temperature was separated out by other weather conditions and boarding percentages. These results highlight the potential micro-environmental challenges encountered with thermal extremes within the trailer and the need to achieve more thermal uniformity throughout the trailer.

Animations representing the temporo-spatial thermal conditions were created to visualize extreme conditions for location and severity over the course of the trips. These animations were compared to the summary variables for consistency.

A summary of recommendations for modifications to TQA were assembled, as well as several areas requiring further research.

Introduction

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). Another reported almost 60,000 pigs experiencing 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% in recent 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. 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 conditions 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).

Trailer Design

There are no standard configurations for commercial swine trailer design in the current pig transport 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.

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; DeShazer et al. 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; DeShazer et al. 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 82 and 93°F (28°C and 34°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 thermal stress for the pigs.

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 welfare status during transport (NPB 2008). Currently, the TQA program is widely used by commercial trucking companies, producers, handlers, and processors. 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 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).

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

Ambient Temperature °F (°C)	Bedding	Boarding (side-slats)	
<10 (-12)	Heavy	90 % Closed	10% Open *
10-19 (-12 ~ -7)	Medium	75% Closed	25% Open *
20-39 (-6 ~ 3)	Medium	50 % Closed	50% Open
40-49 (4 ~ 9)	Light	25% Closed	75% Open
>50 (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, 2008), 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.

Objectives

The main objectives of this study may be summarized as the overall assessment of TQA as applied in a field study, with specific focus on the effectiveness of hot and cold weather management strategies. Specific objectives stated in the original proposal include:

- Determine the effects of trailer bedding depth on skin surface temperature measurements.
- Quantify the insulation value of different bedding depths.
- Determine the effects of trailer boarding on skin surface temperature measurements.
- Quantify the insulative effects of different boarding percentages. (evaluate this by trailer compartment since there can be variation throughout the trailer)
- Determine the effects of fans and/or showering on pig temperature in a stationary trailer.
- Determine the effects of misting method for cooling

Methods

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 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 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 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 2, the numbered zones were 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.

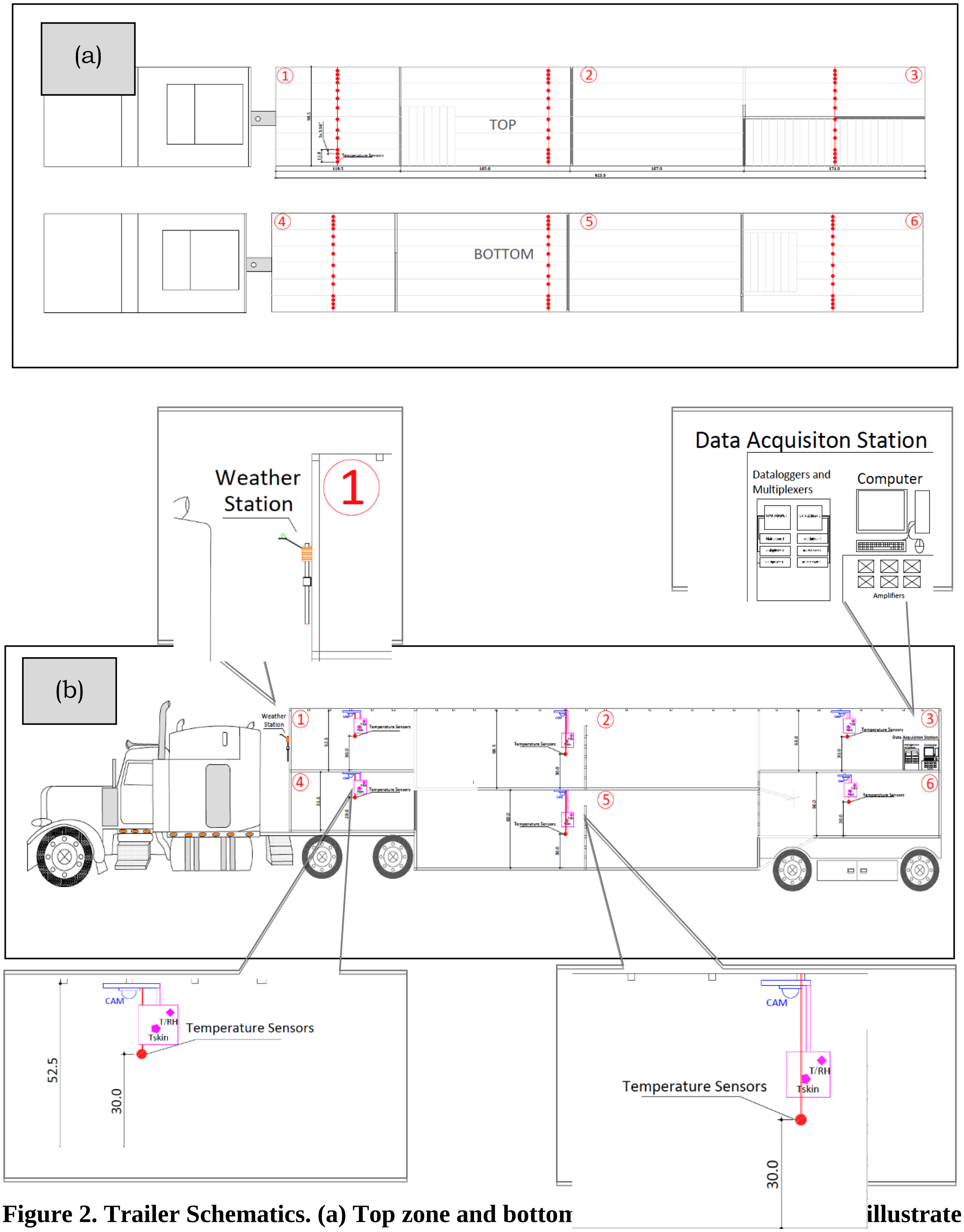

Figure 2. Trailer Schematics. (a) Top zone and botton illustrate the horizontal distribution of sensors in each zone and (b) the left-side elevation view of the six zones and illustrates the vertical distribution of sensors used to capture air temperature, skin temperature, zone-centered temperature/relative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

Trailer Environment Monitoring System

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. The zones represented the upper and lower levels and the front, center, and rear of each, and the sensor locations represented the floor to ceiling space within each area.

A summary of the instrumentation used in the system is presented in Table 2. The placement of each sensor within the trailer is demonstrated in Figure 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 2b).

Table 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

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/unloading periods, and minimal labor for periodic monitoring over the course of a year.

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 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.

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) in all zones to avoid potential damage from the pigs. The pig level air temperature cross-sectional mounts were designed with two configurations owing 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 3b and Figure 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 PVC as protection for the wires, but the sensor were mounted and protruded through the PVC caps into the air space (Figure 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 3b).

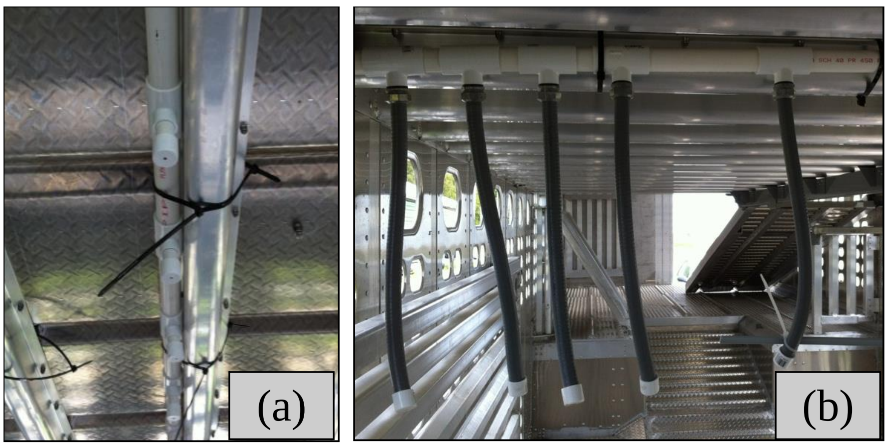

Figure 3. Mounted PVC pipes for thermistors in trailer. (a) Mounted PVC on ceiling in front and rear zones, and (b) the PVC pipes fixed on the ceiling with 14 flex conduits hanging down. The vertical placement with respect to the height above the pigs' back was consistent for all zones within the trailer.

A custom-designed and fabricated instrumentation board (Figure 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 4b). A custom-fabricated metal mesh cage was affixed to the instrumentation board to protect the sensors from potential damage from the pigs.

To protect the computer from vibration during transport, a custom-fabricated enclosure was placed in the corner of the data acquisition center (Figure 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 5b), which avoid undesirable binding of the wires or wear from friction and potential damages from the pigs.

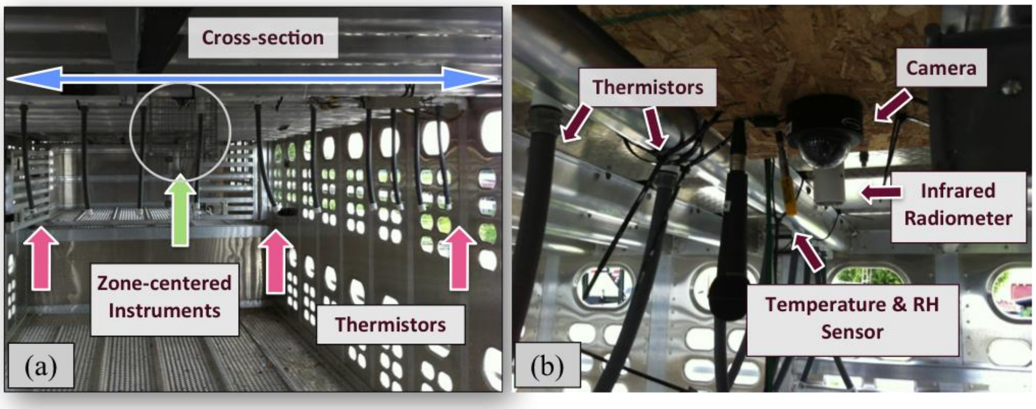

Figure 4. Instrumentation location overview. (a) Trailer cross-section and (b) zone-centered instrumentation board. The zone-centered instrumentation board consisted of one connection box for thermistor sensors and one zone-centered air temperature and relative humidity probe, and one pig exposed surface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

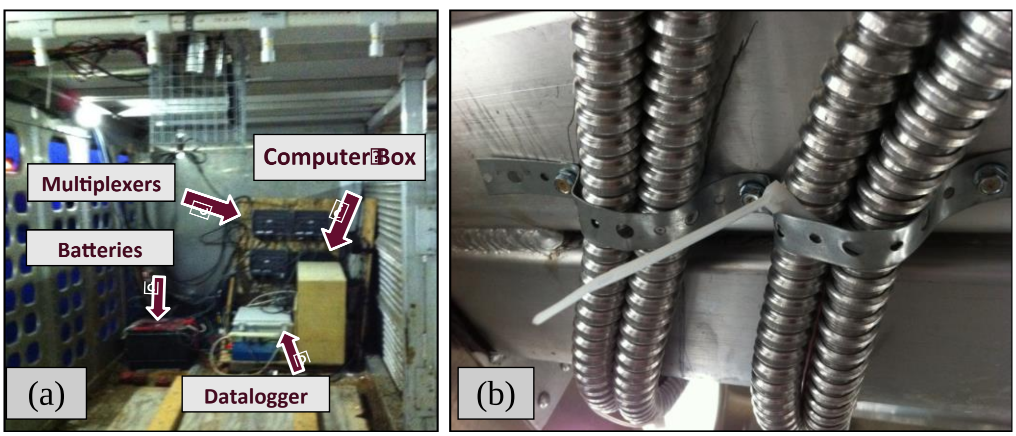

Figure 5. Protection for instrumentation inside the trailer. (a) The protection of data acquisition center, of which consisted of a custom-fabricated computer box with a personal computer inside, three custom-fabricated multiplexers, one datalogger, and two parallel-connected batteries, and (b) the protection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

Instrumentation and Sensor Selection

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 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 -76 to 302°F (-60°C to +150°C) and tolerance 0.36°F (0.2°C). 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 to comprise the trailer internal temperature dataset.

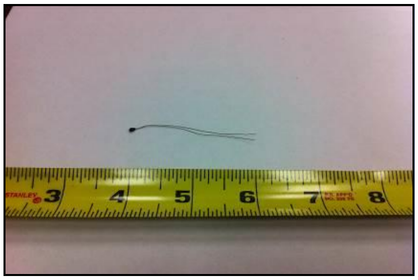

Figure 6. Pig level air temperature sensor (Thermistor, Model No.10M5351, Honeywell Parts). Eighty-four thermistors were implemented in 6 cross-sections within each trailer zone to measure air temperature at pigs level, and located approximately 1.2 m above the trailer floor.

Zone-Centered Air Temperature and Humidity

A combination temperature and relative humidity sensor [(Vaisala INTERCAP HMP60, Vaisala, Vantaa, Finland), Figure 7] was installed centrally at the ceiling within each zone. The zone-centered air temperature and RH sensor operates from -40 to 140°F (-40°C to +60°C) with a typical accuracy of ±1.1°F (±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 7. Zone-centered air temperature and relative humidity (RH) sensor (Vaisala HMP60, Vaisala). Six zone-centered air temperature and RH sensors were implemented at the central area at the ceiling within each of the 6 cross-sections to measure the central air temperature and relative humidity of each trailer zone.

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 8, Apogee SI-111, Campbell Scientific, Logan, UT) within each zone, located at the ceiling center and facing directly downward (Figure 4b).

The infrared radiometer allows a direct measurement of exposed surface temperature without physical contact with the surface being measured. It 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 -67 to 176°F (-55 to 80°C) with an absolute accuracy of ±0.36°F (±0.2°C) from 14 to 149°F (-10°C to 65°C) and ±0.9°F (±0.5°C) from -40 to 158°F (-40°C to 70°C). The half angle field of view is 22° degree, which allows the sensor to cover an approximate 0.1 m^2 area of the exposed skin surface measurement, with a measuring radius of 0.3 m.

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

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 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 to 185°F (-40°C to 85°C) and accuracy of ±1.8°F (±1°C) from -22 to 158°F (-30°C to +70°C) and ±2.3°F (±1.3°C) outside that range.

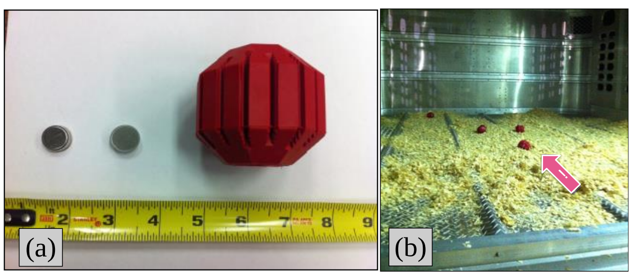

Figure 9. (a) Floor/Bedding Temperature Sensors (iButton DS1921G-F5, Maxim, San Jose, CA) components, and (b) Three to six ibutton sensors ibutton sensors enclosed in protective rubber balls were placed on the bedding within each of the 6 zones at the start of transport to measure the floor/bedding temperature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

Trailer Speed and Location

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.

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.

All 84 thermistor sensors were calibrated over the range from 5 to 113°F (-15 to 45°C) using an environmental controlled chamber against a NIST certified temperature device (Rotronic NT213) for the range 50 to 113°F (10 to 45°C) and a temperature controlled recirculating water bath (Neslab RTE-211, Artisan Scientific Corporation, Champaign, IL) for the range 5 to 50°F (-15°C to 10°C).

Trailer Pre-monitoring Setup Procedure

In cold weather conditions, boarding of trailer openings (Figure 10a) and variation in amount of bedding (Figure 10b) 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.

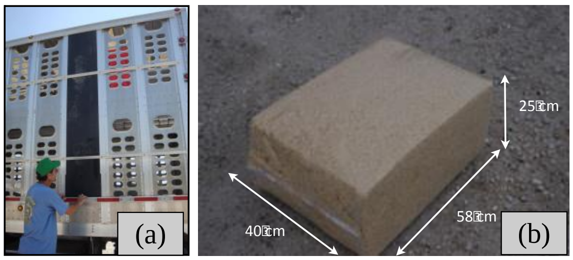

Figure 10. Trailer management strategies for thermal environment inside the trailer during cool and cold conditions. (a) Boarding of the trailer by covering openings and (b) Substrate material (1 bag) that was scattered over the trailer floor prior to each monitoring trip.

TQA Typical and Alternative Boarding Arrangements

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 10a). The boarding coverage recommendations vary from 0-90% and are based on outside temperatures (Table 1).

According to Table 1, 90% boarding with bottom edge covered (Figure 11a) was implemented when ambient temperature was below 10˚F (-12˚C); 75% evenly distributed boarding percentage (Figure 11b) was implemented when outside temperature ranged between 10 to 19°F (-12 and -7°C); 50% evenly distributed boarding percentage (Figure 11c) was implemented when outside temperature ranged from 20 to 39°F (-7 to 4°C); and 25% evenly distributed boarding percentage (Figure 11d) was implemented when outside temperature ranged between 40-49°F (4 and 9°C). For outside temperature that was above 39°F (4°C), the trailer was completely open. For all typical TQA monitoring, boarding was evenly distributed.

Alternative boarding strategies were explored for changing the distribution of the boards and the amount of boarding, when possible. Because the monitoring periods included many duplicate conditions in the 20-49°F (-7-9°C) range, additional arrangement for boarding were applied to explore the effects of boarding distribution on the ventilation patterns within the trailer (Figure 12). For temperature range 20-39°F (-7-4°C), trips with 50% boarding more towards rear (Figure 12a) and trips with 50% boarding all at rear (Figure 12b) were completed; for temperature range 40-49°F (4-9°C), trips with 50% boarding evenly distributed and trips with 25% boarding more towards rear (Figure 12c) were implemented. All of the alternative arrangements were employed with heavy bedding arrangement.

Figure 11. 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 12. Alternative boarding placement arrangements assessed 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.

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

TQA Misting Arrangement

Misting is a cooling strategy applied 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 13a, TX-V626, Teejet Technologies (2 in zone1, 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). Depending on the water pressure applied, a factor of the facilities available, the nozzles in this study could produce either a fog or small droplets.

In this study, two approaches for misting, including misting during loading and misting after loading were evaluated in warm to hot weather conditions. Based on different outdoor temperatures, and availability of water facilities, three misting appraoches were assessed before transport for temperature 80°F (26°C) and above. For monitoring trips that were within 80-90°F (26 to 32°C) outdoor temperature range, misting during loading, misting after loading, and no misting during loading were observed and documented. When the ambient temperature exceeded 90°F (32°C), 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 13b) 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.

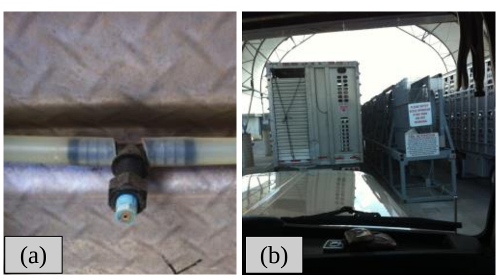

Figure 13. Trailer management strategies for thermal environment of the trailer during warm and hot conditions. (a) Misting nozzles (TX-V626, Teejet Technologies) that were implemented inside the trailer, and (b) trailer location with respect to the fan bank when waiting to unload pigs at the plant.

Data Categorization

Each monitoring trip was summarized by time periods for events with the pigs on the trailer as well as just after unloading (Figure 14). Important 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 present for each time period is shown in Figures 14a and 14c. Prior to each monitoring trip, loading schedules were cooperated with the trucking company, the pork processing plant 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 14. Trailer interior conditions with instrumentation deployed and pigs present 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 and down (DD) pigs were documented for each monitoring trip. The outdoor temperature and relative humidity data were 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 50°F (10°C) were classified as warm/hot trips, while trips monitored when ambient temperature was below 50°F (10°C) were classified as cold trips. According to Table 3, 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.

Trips monitored with boarding in this study were categorized as TQA typical and 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 boarding arrangement combinations were explored to assess the effects of boarding placement on the air distribution within the trailer.

Data Processing

Preliminary Data Processing

The raw data set consisted of two 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); and Part 2) floor temperature (measured by iButton temperature sensors). Raw data Part 1 – downloaded from the Campbell Datalogger CR23X after each monitoring day (typically 1 to 3 trips). Raw data Part 2 were downloaded after every full monitoring period (typically 5 to 7 trips).

The raw data set was manually separated by the 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.

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.

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 ±95°F (±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 ±95°F (±35°C) was selected as the acceptable range based on a manually assessed signal output when sensor connection failures were observed.

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).

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 50°F (10°C) lower than the outside temperatures. Thus, any data points that were lower than outside temperature minus 50°F (10°C) were removed from dataset.

Data Analysis

Overall Characteristics of Thermal Environmental Data

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.

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} <5°F;-15°C), cold (5°F < T_{in} < 32°F; -15°C < T_{in} < 0°C), cool (32°F < T_{in} < 64°F; 0°C < T_{in} < 18°C), thermoneutral (64°F < T_{in} < 77°F; 18°C < T_{in} < 25°C), warm (77°F < T_{in} < 86°F; 25°C < T_{in} < 30°C), hot (86°F < T_{in} < 95°F; 30°C < T_{in} < 35°C), and extreme hot (T_{in} >95°F; 35°C).

The Temperature-Humidity Index (THI) was processed with Equation 1, using the zone-centered air temperature and relative humidity to calculate THI and classify based on livestock weather and safety index conditions (LWSI) (LCI 1970; Brown-Brandl et al. 1997; DeShazer et al. 2009; Hahn 1995; St-Pierre et al. 2003)]. The THI values were categorized according to the Livestock Weather Safety Index into four LWSI ranges: Normal (THI ≤ 74), Alert (75 ≤ THI ≤78), Danger (79 ≤ THI ≤ 83) and Emergency (THI ≥84) (NRC, 1981; LCI, 1970; DeShazer et al., 2009).

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

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 categorical ranges. Each cell within the table corresponding to a given temperature or LWSI category 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 safety condition 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.

Temperature Distribution Inside the Trailer

Temperature distribution patterns were assessed as an indicator of the ventilation patterns within the trailer. Cooler regions indicated 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 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 appeared on the animation to notify events occurred in the monitoring trip.

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 data were included in these analyses, and were further specified into extreme cold-temperature trips, cool/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.

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.

Effects of Bedding Depth on Pig Skin Temperature

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 bedding depth on pig skin temperature. Two summaries were completed: 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.

This analysis did not look at floor temperatures for specific zones within the trailer because the floor sensors were able to move around the trailer and it was unknown where each was at each measurement point. This analysis provides a broader look at the trailer environment. Deviations from a linear relationship between the air temperature and skin temperature would indicate that the bedding provides some contribution to the environmental conditions.

Effects of Boarding Percentage on Pig Skin Temperature

The trailer internal zone-centered air temperatures and pig skin temperatures were processed and categorized for all completed monitoring trips to evaluate the effects of boarding percentage on pig skin temperature. The relationship between pig skin temperature, variable trailer boarding percentage arrangement, and corresponding zone-centered air temperature were plotted in a scatterplot.

Of all the trips evaluated, the following analyses were completed: the minimum pig skin temperature observed *during transport period*; the maximum pig skin temperature 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 relationship between the minimum and the maximum pig skin temperature and the corresponding boarding percentage were explored in scatterplots to illustrate the impact 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. A linear relationship would be expected if the boarding had no impact on internal trailer temperature, and deviations indicate conditions altered due to the boarding.

Effects of Short Breaks During Transport on Trailer Thermal Environment

During the transport period with pigs on the trailer, the truck 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 breaks on trailer thermal environment, a scatterplot was generated for one monitoring trip chosen under mild weather conditions (outside temperature ranged from 50 to 69°F (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.

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-specific skin temperature distribution for hot weather conditions, zone-specific 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-specific skin temperature distribution and THI distribution analyses, the same methodologies applied for overall zone-specific skin temperature distribution for all monitoring trips evaluated were applied.

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 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 15, 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 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.

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.

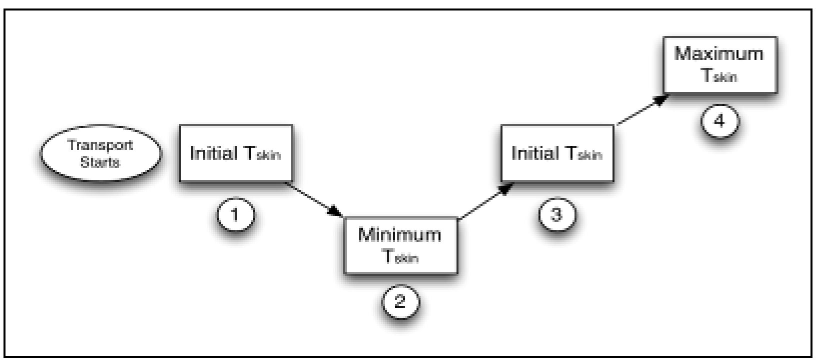

Figure 15. Events to determine the effectiveness of misting before transport for cooling practices. At each event, the skin temperature, and the time at which the skin temperature occurred were recorded.

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, DD (dead and 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.

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 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 analyzing 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 likely reached freezing conditions were calculated.

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 analysis was completed as was completed for TQA typical boarding percentages. For both the monitoring trips with TQA typical and alternative boarding percentage, 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 and 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 on 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 $\alpha=0.05$.

Results and Discussion

Overall Characteristics of Trailer Thermal Environmental Data

Monitoring Trip Completion Summary

With trailer management based upon the TQA guidelines (Table 1), 43 monitoring trips were completed from May 2012 to February 2013. Of these, 30 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 30 TQA typical and the 12 alternative boarding monitoring trips for analyses considering air temperature and THI assessment, and excludes the 1 trip that experienced air temperature sensor failures. 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 boarding arrangements for monitoring and the numbers of completed trips corresponding to specific temperature ranges are included below (Tables 3 and 4).

Table 3. Summary of external environmental temperature and corresponding trailer management for 31 monitoring trips with typical TQA guidelines.

Temperature °F (°C)	Trailer Management			Number of Completed Loads
	Bedding	Boarding	Misting	
<10 (-12)	Heavy	90% with bottom open		4*
10-19 (-12 ~ -7)	Heavy	75% Evenly Distributed		1
20-39 (-7 ~ 4)	Heavy	50% Evenly Distributed		3
40-49 (4-9)	Heavy	25% Evenly Distributed		3
50-69 (10-20)	Medium	0%	No Misting	6
70-79 (21-26)	Medium	0%	No Misting	2

80-89 (27-31)	Medium	0%	Misting After Loaded	3
	Medium	0%	Misting During	3
	Light	0%	No Misting	1
>90 (32)	Light	0%	Misting After Loaded	3
	Light	0%	Misting During	2
Total				31

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

Table 4. Summary of external environment temperature and corresponding trailer management for 12 monitoring trips with variations from typical TQA boarding distribution.

Temperature °F (°C)	Trailer Management			Number of Completed Loads
	Bedding	Boarding	Misting	
20-39 (-7~4)	Heavy	50% More Towards Rear	No Misting	3
	Heavy	50% All at Rear	No Misting	3
40-49 (4-9)	Heavy	50% Evenly Distributed	No Misting	3
	Heavy	25% More Towards Rear	No Misting	3
Total				12

Overall Dead and Down Summary

For all the monitoring trips evaluated, the number and location within the trailer of dead and down (DD) pigs for each monitoring trip were documented upon arrival at the abattoir. The information corresponding to outdoor conditions and trailer management is summarized in Table 5.

Table 5. Summary of pigs dead and down (DD) for all monitoring trips with trailer managed according to TQA guidelines.

Outside Temperature °F (°C]	Trailer Management	Transport Duration (h)	Pig Skin Temperature		DD *(n)	Corresponding Location
			min (°C)	max (°C)		

20-39 (-7~4)	Boarding, 50% More Toward Rear	2.38	11.6	31.0	1[A]	Zone 6
40-49 (4-9)	Boarding, 25% Evenly Distributed	2.50-3.0	14.3-19.6	30.7-34.5	2[A, 1]	Zone 2
80-89 (27-31)	No Misting	1.62	30.5	39.4	1[B]	Unknown[2]
> 90 (32)	Misting, during loading	3.10	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 (DD) upon arrival at the abattoir (approximately 0.06% of the total pigs transported). The occurrences of DD were not concentrated for any outdoor condition or management strategy. Of all five trips that encountered DD 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.

Duration of Transport Phases with Pigs on the Trailer

Figure 16 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 Figure 16 corresponds to the three events, and the x-axis corresponds to the durations of each event shown in hours.

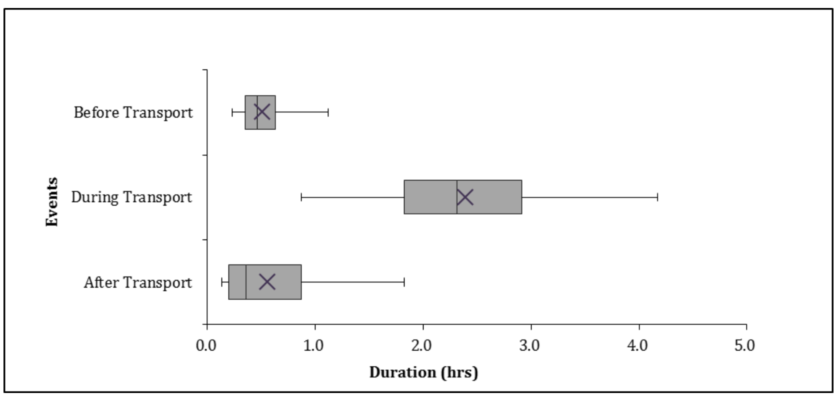

Figure 16. Distribution of event durations with pigs on the trailer, including before transport, during transport and after transport for all 43 monitoring trips. In the box and whisker plot, X indicates the mean duration for each event, and the box and whiskers indicate the 0, 25, 50, 75, and 100 frequency percentiles.

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

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, short transport duration (≤3 h) can result in more negative effects concerning pig well-being during road transportation compared to long duration transport (>3 h) (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 h and 2.9 h, and for 25% of the events the road-transport duration exceeded 2.9 h. 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.

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 for the purpose of evaluating hot and cold management practices. Of the trips evaluated, a broad range of temperature and temperature-humidity index levels was measured (Tables 6 and 7).

For the 20 warm/hot-temperature trips evaluated (Table 6), 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 90°F (32°C), 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.

In terms of LWSI (Table 7), 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 70°F (21°C), 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 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 6. Assessment of trailer environment based on grouping all pig-level air temperature measurements into thermal comfort classifications for all transport events 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: $T_{in} < 5°F$ (-15°C); [2] Cold: 5°F (-15°C) < T_{in} < 32°F (0°C); [3] Cool: 32°F (0°C) < T < 62°F (18°C); [4]Thermoneutral: 62°F (18°C) < T < 77°F (25°C); [5] Warm: 77°F (25°C) < T < 86°F (30°C); [6] Hot: 86°F (30°C) < T < 95°F (35°C); [7] Extreme Hot: T > 95°F (35°C).

Table 7. Assessment of trailer environment based on grouping measurements into Livestock Livestock Weather Safety Index (LWSI) based on Temperature and Humidity Index (THI) for all transport events when pigs were present 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 THI Safety Analysis			
				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

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 90°F (32°C), 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 80-89°F (26 to 32°C), 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 80°F (27°C) or was less than 40°F (5°C). 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 6 and 7 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.

Temperature Distribution inside the Trailer

Figures 17, 18, and 19 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 loading period at swine barn, during transport period when trailer was on the road, and prior to unloading period when the trailer was stopped at the abattoir. The range of temperatures provides insight into airflow patterns within the trailer. The snapshot represents 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 of which the ambient temperature range was above 90°F (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.

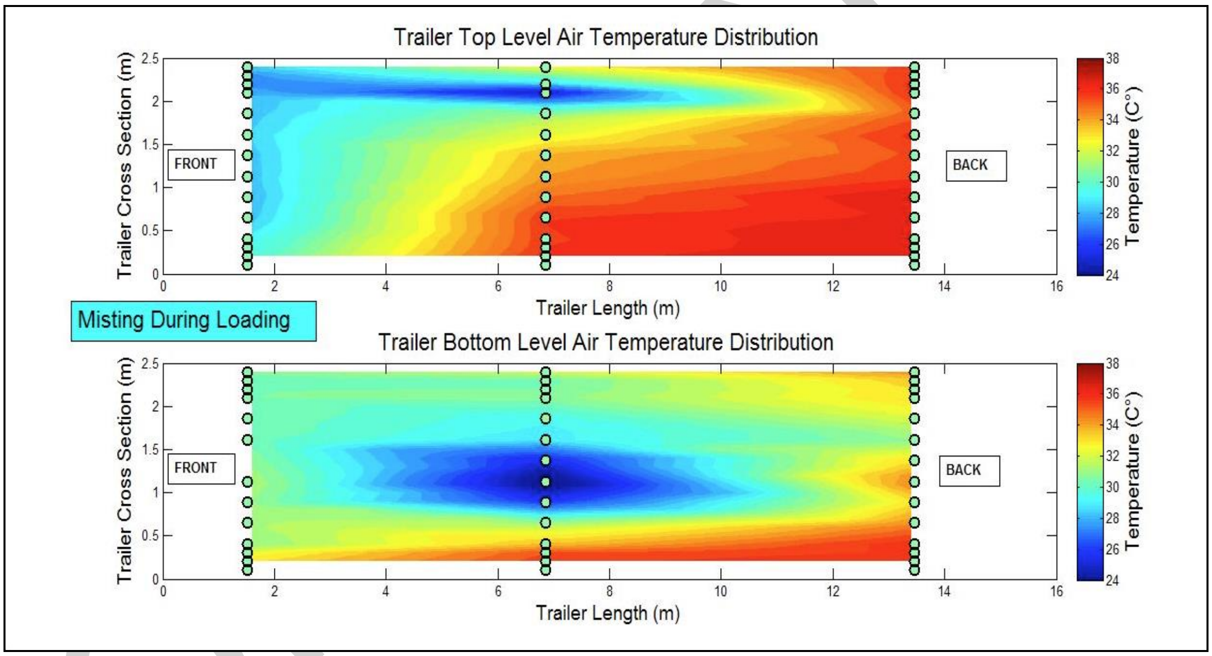

Figure 16. Temperature distribution at one point in time from an animation of a monitoring trip when misting was applied during the loading period when the trailer was stopped at the swine barn. The corresponding monitoring trip was categorized as an extreme hot-temperature trip for which the ambient temperature range was above 90°F (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.

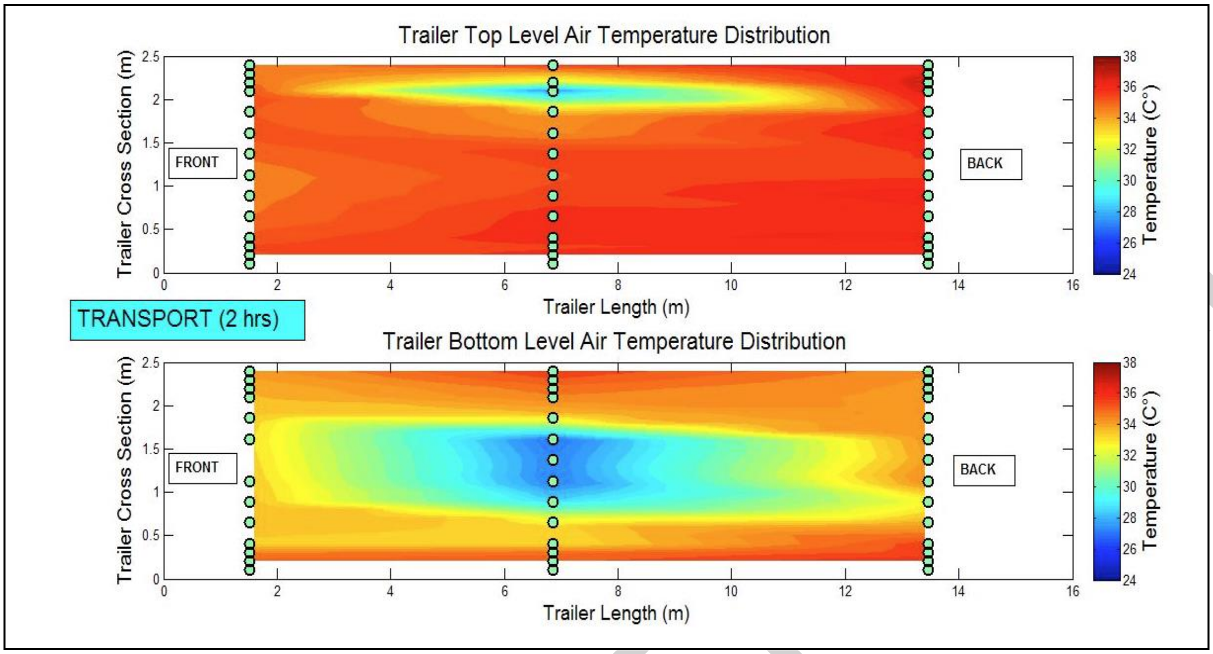

Figure 17. Temperature distribution at one point in time from an animation of a monitoring trip during the transport period after misting at swine barn. The corresponding monitoring trip was categorized as an extreme hot-temperature trip for which the ambient temperature range was above 90°F (32°C). 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.

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.

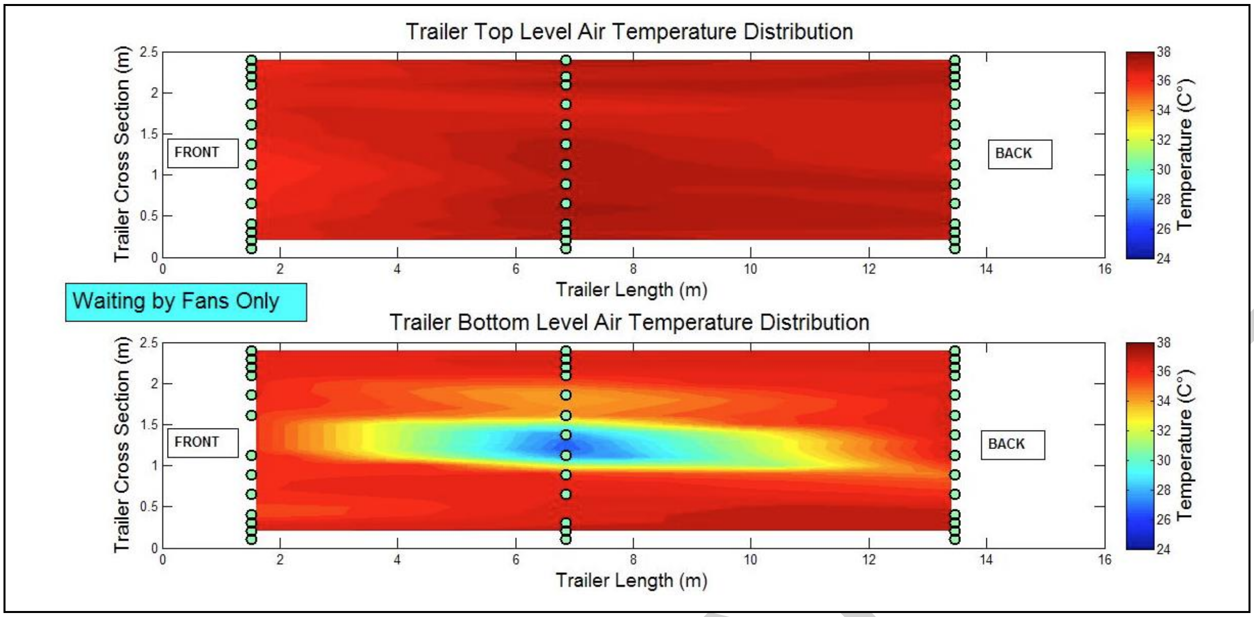

Figure 18. Temperature distribution at one point in time from an animation of a monitoring trip when the trailer was stopped at the abattoir with external fans. The corresponding monitoring trip was categorized as an extreme hot-temperature trip for which the ambient temperature range was above 90°F (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.

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 as low as 59°F (15°C) that can cause chilled pigs was observed in the lower level, despite a high ambient temperature of 95°F (35°C) (Figure 19). 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.

Overall Zone-specific Skin Temperatures

Figure 20 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.

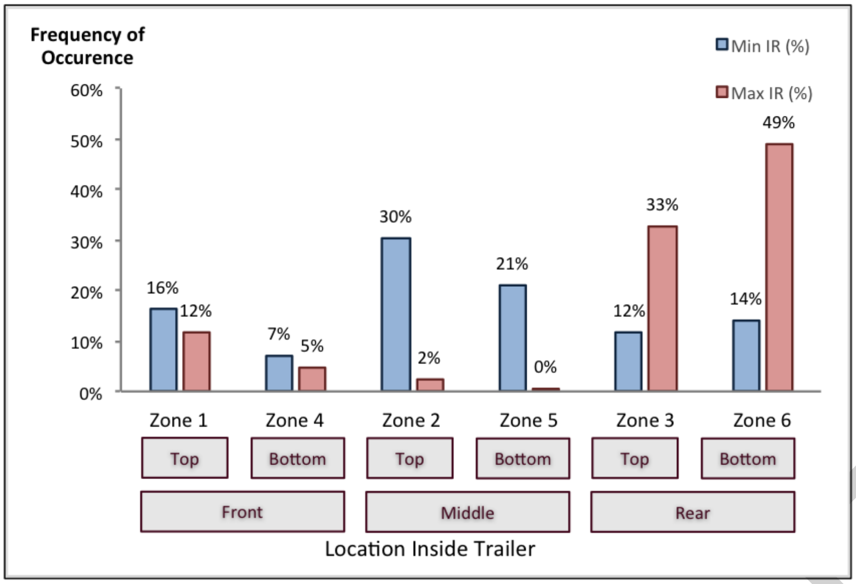

Figure 20. Location of maximum and minimum skin temperatures within the trailer for 42 monitoring trips over outside temperatures ranging from 7 to 100°F (-14 to 38°C). The rear compartments consistently resulted in the warmest skin temperatures on the trailer, and the middle compartments consistently resulted in the coolest skin temperatures on the trailer, regardless of outdoor weather conditions. 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.

Overall Floor Temperature Distribution

Of the 43 monitoring trips evaluated, the overall floor temperatures ranged from 0 to ~100°F (-18 to ~ 40°C) (Figure 21). 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.

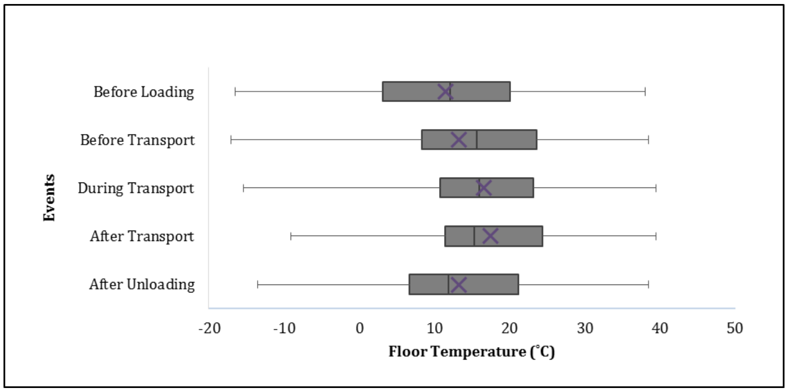

Figure 19. Overall distribution of averaged floor temperature from each trip for before, during, and after pigs were on the trailer for all monitoring trips. X indicates the average value of floor temperature, and the box and whiskers indicate the 0, 25, 50, 75, and 100 frequency percentiles.

This overall floor temperature distribution analysis revealed that on average, some pigs experienced a warm to hot floor/bedding temperature within the trailer, and some pigs experienced freezing bedding and floors at some point during every phase of the transport process. 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.

Effects of Trailer Bedding Depth on Skin Surface Temperature

The effects of light, medium, and heavy bedding on pig's skin surface temperature were evaluated and summarized in Figure 22. 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 22, 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.

The scatterplot shown in Figure 22 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 8 to 113°F (-13 to 45°C). Depth of bedding, trailer interior air temperature, and the interaction of bedding and air temperature on DOA, NA and DD 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} <32°F (0°C)), or more than 3 bags during mild weather (32°F < T_{out} < 70°F; 0°C < T_{out} < 21°C). An increase in the DOA rate was recorded for adding more than 3 bags of bedding for warm weather (T_{out} > 70°F; 21°C). 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 floor was not explored.

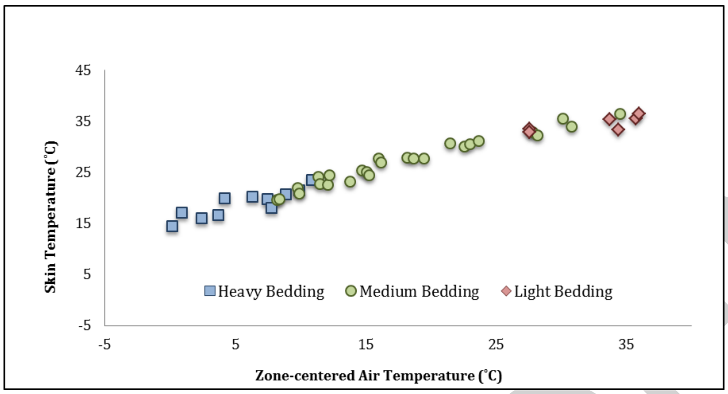

Figure 20. Skin surface temperature versus corresponding zone-centered air temperature taken for different bedding depths, including measurements taken before transport, during transport and after transport during 43 monitoring trips over temperatures ranging from -14 to 38°C.

The 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.

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 23). In Figure 23, the maximum and minimum pig skin temperatures are plotted against the corresponding zone-centered air temperatures observed for the same location and time. 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.

As shown in Figure 24, 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

93°F (34°C), 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.

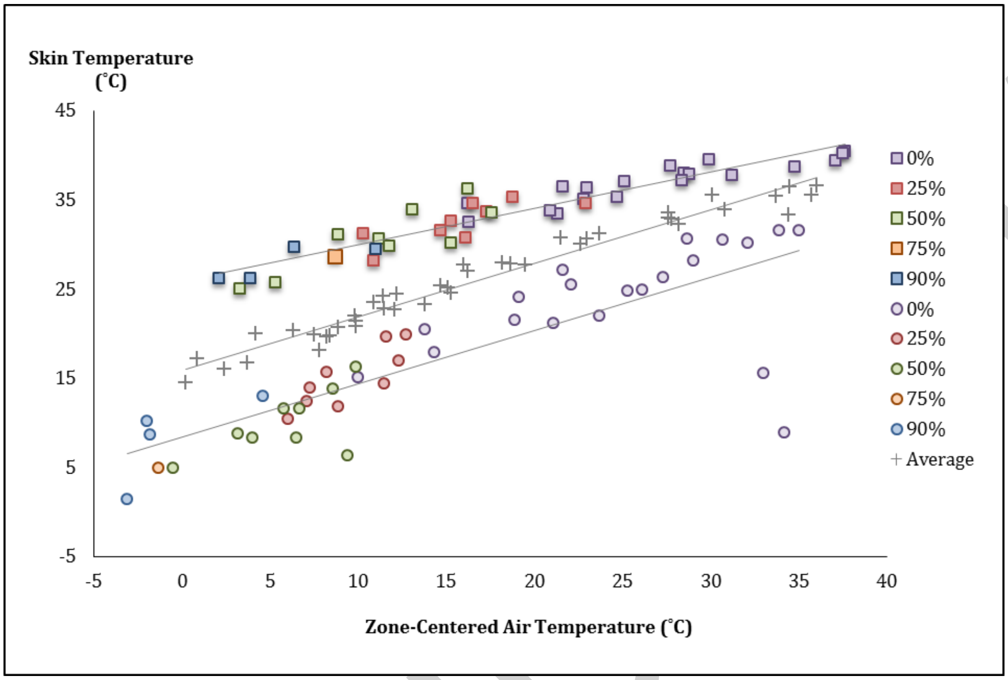

Figure 21. Overall effects of trailer boarding variations (including 0-90%) on pig skin temperatures during transport. The maximum and minimum skin temperatures are plotted against zone-centered air temperature. The maximum skin temperature and the minimum skin temperature are represented by squares and circles, respectively. Different trailer boarding variations are represented by identical shapes with different colors. The average skin temperature is included on the figure as a reference.

These results further agree with the results discussed previously, 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.

Effects of Short Breaks during Transport on Trailer Thermal Environment

The effects of short breaks on trailer thermal environment during transport with pigs on the trailer for one monitoring trip during mild weather conditions (70 to 80°F; 21 to 26°C) was explored and summarized in Figure 24.

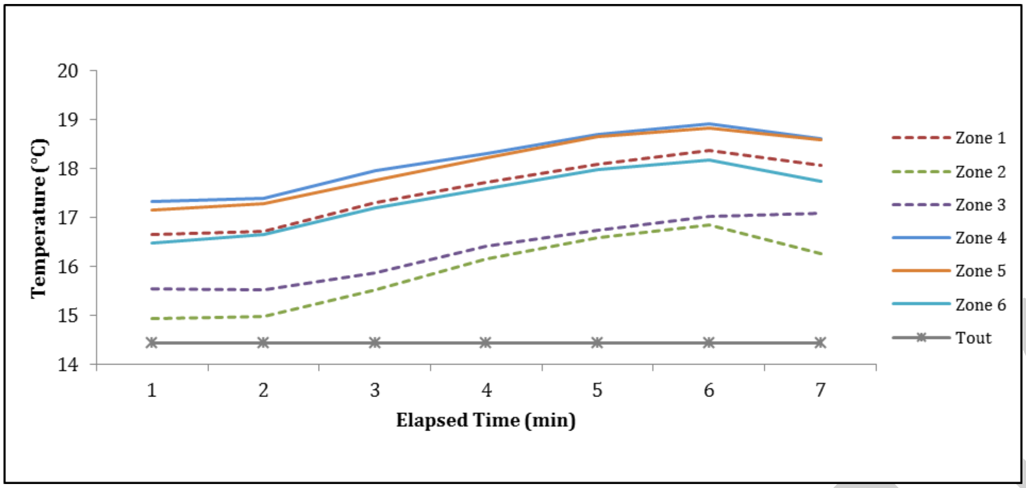

Figure 22. Trailer interior zone-centered air temperature and outside temperature change during mild ambient weather conditions (70 to 80°F 21 to 26°C) during short breaks with pigs on the trailer for during transport period.

From Figure 24, stopping for breaks resulted in rapid temperature increases for all 6 zones within the trailer, with a temperature rise of almost 1.8°F/min (1°C/min) with a 5-7°F (3-4°C) 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 2 to 4°F (1 to 2°C), 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 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).

Supported by 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, though the implications of this change were not explored in this study. The implications of this approach were not explored in this study, such as impacts on gas concentrations or animal fatigue.

Assessment of Current TQA Guidelines for Hot Weather Conditions

Zone-specific Skin Temperature Responses for Hot Weather Conditions

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 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 6, while only a small portion (< 30% for 63% of the trips evaluated) of duration of transport experienced thermoneutral (65 $<T_{in} <$ 77°F; 18 $<T_{in} <$ 25°C), the majority of the trailer experienced warm through hot conditions ($T_{in} >$ 77°F; 25°C). 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.

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 25).

As shown in Figure 25, 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 constant, 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.

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 and THI); (2) pig skin temperature reduction between initial and minimum skin temperature; and (3) the time duration elapsed between critical skin temperatures. Table 8 summarizes pig skin temperature reduction by the two misting approaches applied at the farm prior to the transport period.

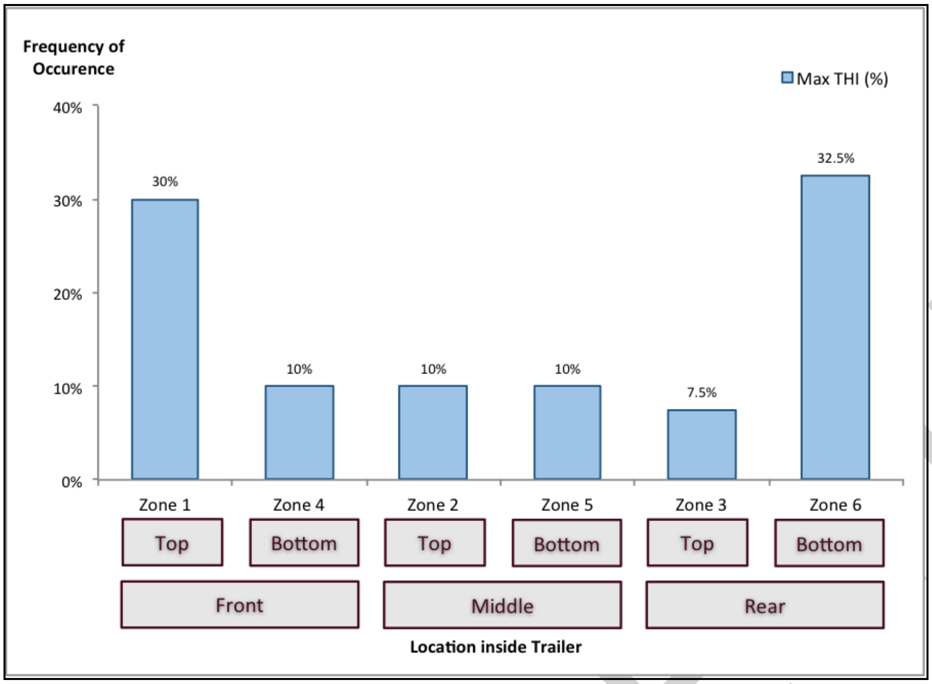

Figure 23. Specific zone location of maximum THI in the trailer for 20 hot temperature trips. Zone 1 and Zone 6 resulted in the highest maximum THI measurements.

Table 8. 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 represent the summary of cooling behavior.

Misting Arrangement	Misting Duration (min)	ΔT_{skin} (°F, °C)	Time to min T_{skin} (min)	Time to initial T_{skin} (min)	Time to max T_{skin} (min)	Max THI
After Loaded (n=6)	5-12	1.4-16.7, 0.8-9.3	7-18	5-11	17-162	83-97
During Loading (n=5)	20-60	4.0-28.8, 2.2-16	1-12	4-11	4-151	82-96

Skin temperature reduction (ΔT_{skin}) shown in Table 8 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 8, 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 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 in this study. 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 this 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.

Effectiveness of Fans with and without Misting in a Stationary Trailer 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. 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 26 through 28 and Table 9. In addition, trailer internal zone-centered air temperature change was computed for each observation (Table 10). Temperature drops and wet-bulb temperature depression for each observation are summarized in Table 10.

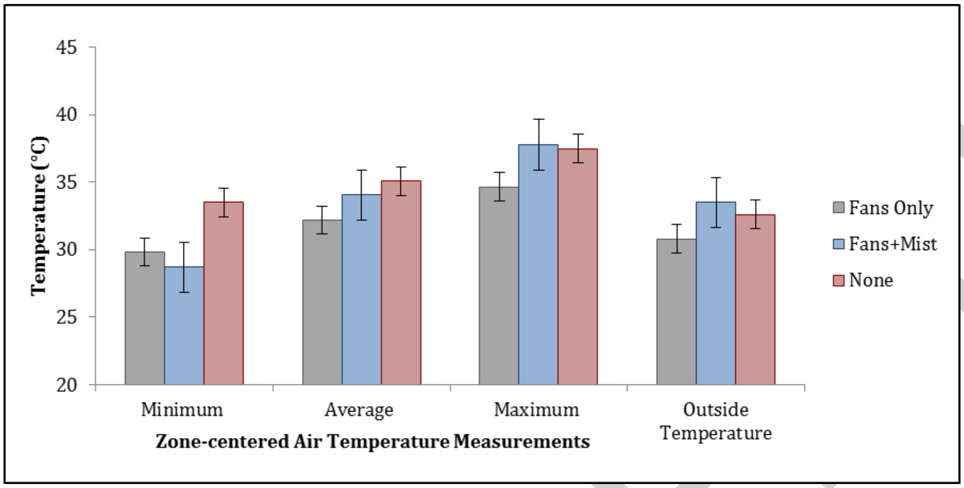

Figure 24. Effectiveness of two cooling methods (fan operation external to stationary trailer and fan operation with misting inside the trailer) or nothing on zone-centered air temperature during hot ambient weather conditions while waiting to unload pigs at the abattoir. Effects are characterized by 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 9.

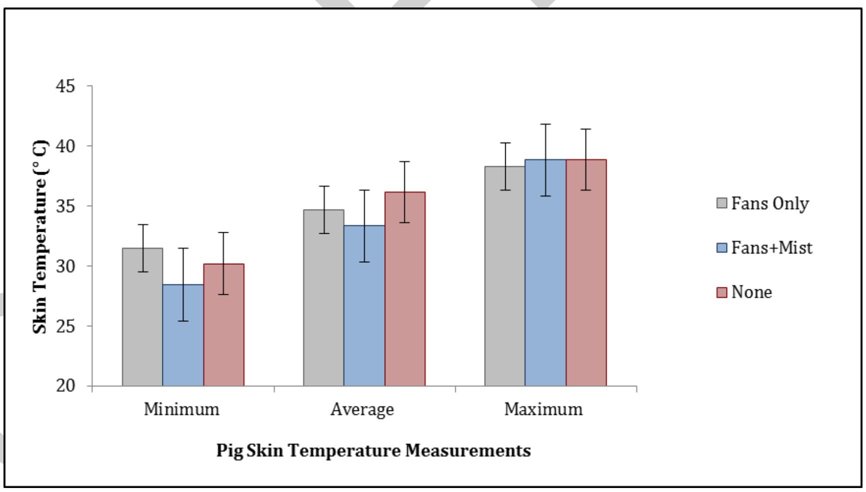

Figure 25. Effectiveness of two cooling methods (fan operation external to stationary trailer and fan operation with misting inside the trailer) or nothing on pig skin temperature during hot ambient weather conditions while waiting to unload pigs at the abattoir. Effects are characterized by the minimum, 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 9.

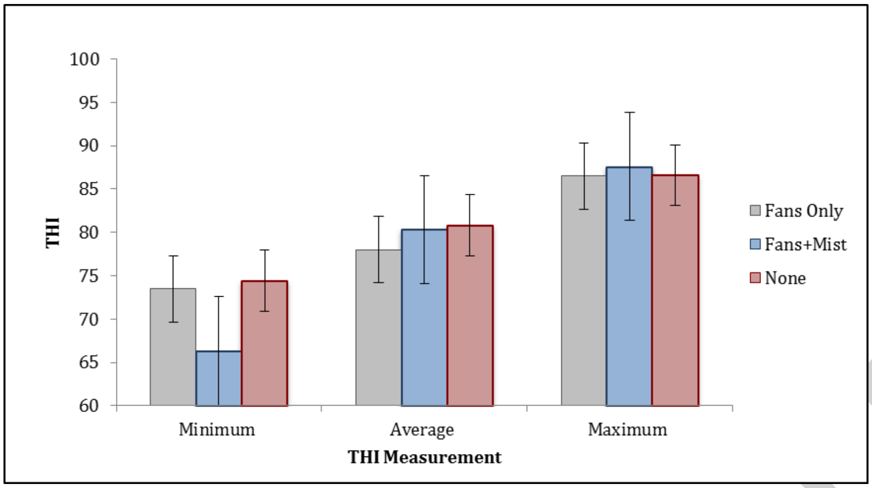

Figure 26. Effectiveness of two cooling methods (fan operation external to stationary trailer and fan operation with misting inside the trailer) or nothing on THI measurements during hot ambient weather conditions while waiting to unload pigs at the abattoir. Effects are characterized by the minimum, average, and maximum THI that occurred at any point inside the trailer for each cooling approach. Supplemental information and characteristics are noted in Table 9.

Table 9. 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 26 through 28.

Events	Outside Temperature (°F, °C)				Duration (h)	Number of Observations (n)
	Mean	SD	Min	Max		
Fans only	87.4, 30.8	7.7, 4.3	78.8, 26.0	95.7, 35.4	0.7 ± 0.2	4
Fans + Misting	92.3, 33.5	8.8, 4.9	82.2, 27.9	98.9, 37.2	0.4 ± 0.2	3
None	90.7, 32.6	0.36, 0.2	82.2, 27.9	98.9, 37.2	0.4 ± 0.2	5

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 26, 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 10). A similar trend was observed for pig skin temperature (P = 0.15 - 0.84 for three mean separations) (Figure 27). The best-case scenario shows the potential that the responses from all observations were below the onset 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 28) 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 3 to 5°F (2 to 3°C) average compartment air temperature reduction inside the trailer. For the best case scenarios reported in Table 10, a similar reduction of 2 to 5°F (1 to 3°C) 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 humidities 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 as low as 59°F (15°C) was observed for pigs that had been exposed in hot trailer zone-centered air temperatures (up to 106°F, 41°C, 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.

Table 10. Temperature change resulting from cooling approaches within the trailer for all six zones inside the trailer while waiting at the abattoir between transport and unloading.

Methods	Trip ID	Observation	Temperature Drop[1] (°F, °C)						WBD[2] (°C)
			Zone 1	Zone 2	Zone 3	Zone 4	Zone 5	Zone 6	
None	M2-4[B]	1	-3.8, -2.1	-6.3, -3.5	-5.9, -3.3	0.0, 0.0	-2.2, -1.2	-2.5, -1.4	23.0, 12.8
	M2-5	2	-0.7, -0.4	-2.2, -1.2	-3.1, -1.7	-1.3, -0.7	-1.3, -0.7	-2.7, -1.5	13.7, 7.6
	M3-1[A]	3	0.9, 0.5	*NA*[*]	0.9, 0.5	0.2, 0.1	0.7, 0.4	0.9, 0.5	20.0, 11.1
	M3-6	4	*NA*[*]	-1.1, -0.6	-1.3, -0.7	-0.4, -0.2	-0.2, -0.1	-0.5, -0.3	25.0, 13.9
	M3-7	5	*NA*[*]	-2.9, -1.6	-2.9, -1.6	-1.4, -0.8	-1.1, -0.6	-1.4, -0.8	23.9, 13.3
Fans Only	M2-1	1	0.7, 0.4	0.7, 0.4	1.3, 0.7	2.9, 1.6	4.0, 2.2	6.5, 3.6	19.8, 11.0
	M3-3	2	*NA*[*]	2.7, 1.5	2.0, 1.1	-0.9, -0.5	-0.2, -0.1	0.4, 0.2	21.1, 11.7
	M3-7	3	*NA*[*]	3.6, 2.0	0.0, 0.0	-0.2, -0.1	0.4, 0.2	-0.2, -0.1	24.1, 13.4
	M4-6	4	2.3, 1.3	1.6, 0.9	1.6, 0.9	-0.5, -0.3	0.7, 0.4	0.0, 0.0	8.5, 4.7
Fans + Mist	M2-1	1	1.4, 0.8	1.1, 0.6	0.9, 0.5	-2.3, -1.3	-2.5, -1.4	-5.9, -3.3	20.3, 11.3
	M2-4[B]	2	1.1, 0.6	5.8, 3.2	6.3, 3.5	-1.8, -1.0	1.1, 0.6	2.3, 1.3	23.0, 12.8
	M3-1[A]	3	-2.0, -1.1	*NA*[*]	-1.1, -0.6	-1.1, -0.6	-0.5, -0.3	-1.3, -0.7	20.2, 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.

Assessment of Current TQA Guidelines for Cold Weather Conditions

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 and 4 extreme cold-temperature trips[2] followed a similar trend to that presented for the overall skin temperature distribution.

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 6, while only a small portion (0.2 to 10.2% for 70% of the trips evaluated) of duration of transport experienced cold ($5 < T_{in} < 32$°F; $-15 < T_{in} < 0$°C), the majority of the trailer stayed within cool condition range ($32 < T_{in} < 65$°F; $0°C < T_{in} < 18°C$), which may not create a high risk for complications for road transport under 3 h.

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.

Effects of Heavy Bedding on Trailer Thermal Environment

Of all 43 completed monitoring trips, 11 were arranged with heavy bedding, 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 with these conditions. The effects

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

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 29, and corresponding supplemental statistics are provided in Table 11.

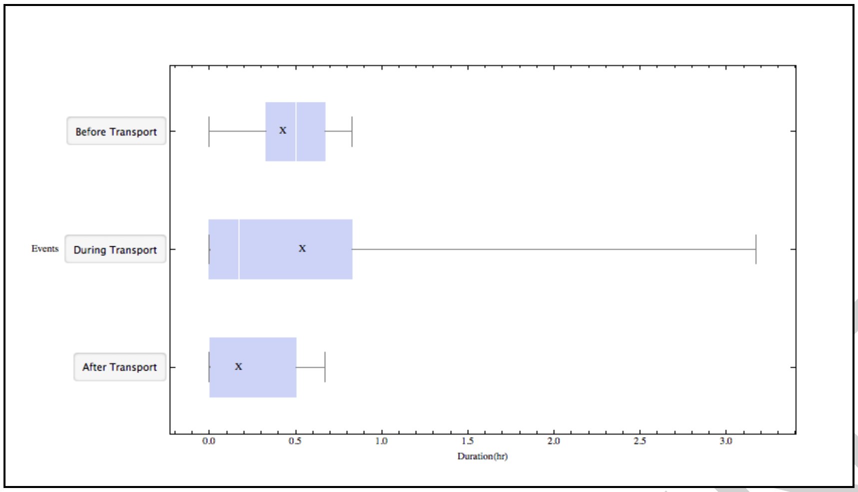

Figure 27. Overall distribution of floor temperatures while pigs were on the trailer with heavy bedding, including before transport, during transport, and after transport for 8 trips that were observed under extreme cold conditions.

Table 11. 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 29.

	Before Transport (h)	During Transport (h)	After Transport (h)
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 6). The measurement of floor/bedding temperatures represents another measure of the micro-environmental conditions experienced by the pigs on the trailer. 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 h before transport and after transport periods and ranged from 0 to 3.2 h during transport. Average duration for before transport, during transport and after transport was 0.4 h, 0.6 h, and 0.2 h, 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 h. Dead and down pigs are more prone to occur under more extreme conditions. An extreme occurrence as long as 3.2 h in the maximum duration for during transport period was recorded and resulted in the skew observed in the box-and-whisker plot (Figure 29). 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. On the contrary, a minimum amount of bedding is beneficial to limit the pig contact with the floor. On short-duration trips, pigs have been shown to not lie down, but the bedding coverage would be more important for longer-duration trips if pigs do lie down.

Further exploration of the temperatures (Figure 30) 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.

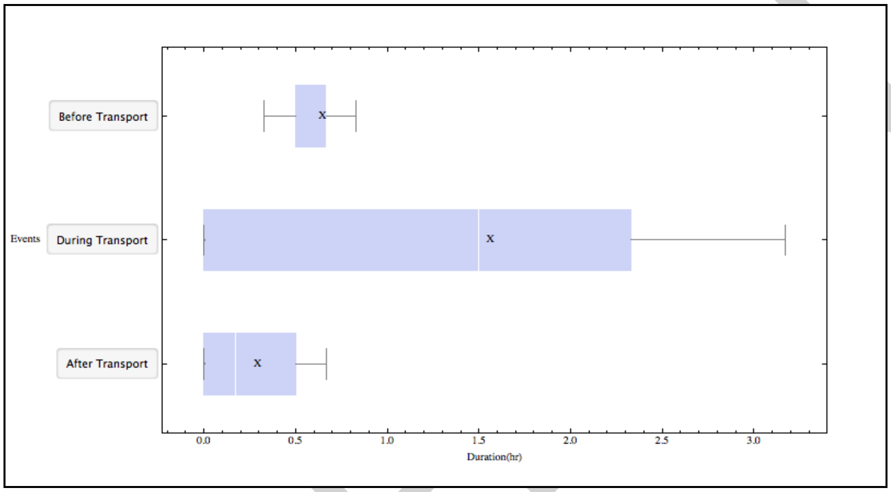

Figure 30. Maximum distribution of subzero floor temperatures for the floor sensor on each trip with the longest duration of subfreezing floor temperature in the trailer with heavy bedding, including before transport, during transport and after transport for 8 monitoring trips over extreme cold conditions. Supplemental information is noted in Table 12.

Table 12. 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 (h)	During Transport (h)	After Transport (h)
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 h before transport and after transport periods, and the range stays within 0.3 to 0.8 h and 0 to 0.7 h, respectively. The average worst-case scenario for before transport, during transport and after transport was 0.6 h, 0.6 h, and 0.3 h, respectively.

Compared to overall subfreezing floor temperature distributions (Figure 29), although the bounds of the floor temperature distributions are similar, for before transport and after transport periods, the average floor temperatures are higher, 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 h during the transport period. For the worst-case scenario, the minimum values of the floor subfreezing durations (Figures 29 and 30) indicating freezing 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 within 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 resulting 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 it.

Figure 31 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 (10°F, -12°C). For 75% of the time, bedding materials cooled to subfreezing conditions in less than 0.5 h, with a minimum duration of 0 h, and a maximum duration of 2.7 h. One approach to avoid or reduce this potential condition would be to start every trip with fresh bedding, though this may not always be practical from either a logistics or an economic standpoint.

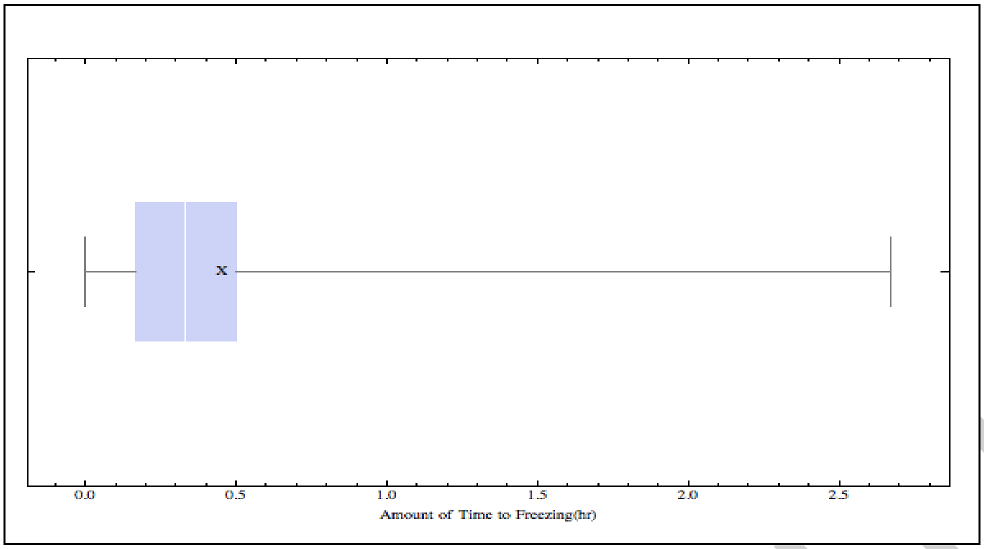

Figure 31. Distribution of the amount of time for bedding to reach freezing conditions between unloading and the next loading for 5 monitoring trips over the coldest temperature range.

A summary of the times for the trailer floor to reach subfreezing condition between the abattoir and the next farm is included in Table 13. 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 h. 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 h. 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 h.

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 13. 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 (h)
Time for first sensor in trailer to reach freezing temperature	0.10 (h)
Time for last sensor in trailer to reach freezing temperature	1.50 (h)

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.

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.

Effects of Boarding Distributed More Toward 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 20 to 40°C (-7 to 4°C). The results are summarized in Figure 32.

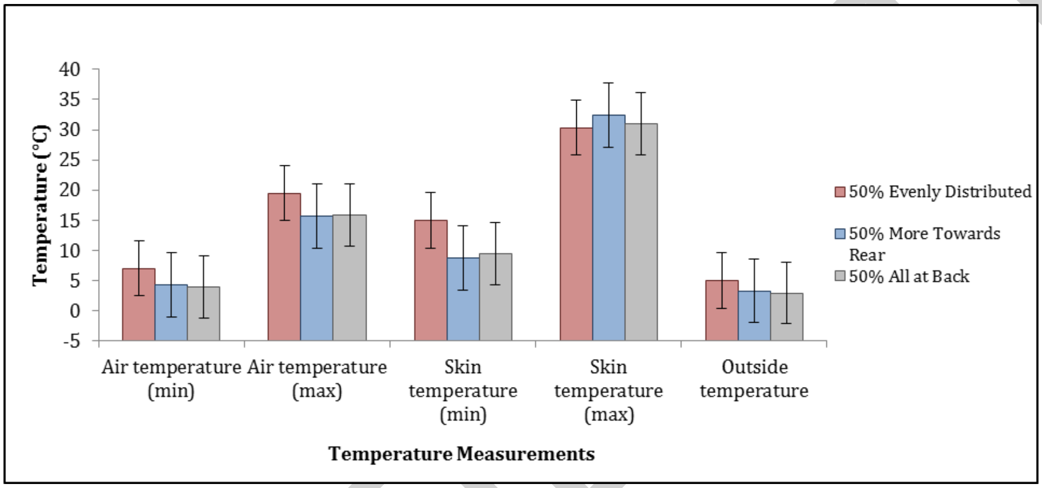

Figure 32. Effects of 50% boarding with three different boarding placement arrangements, including evenly distributed (typical TQA implementation, n=2), more towards rear (n=3), and all at rear (n=3). Responses assessed were minimum and maximum zone-centered air temperature measuerements and the minimum and maximum skin temperature . Observations were made under the outside temperature range of -7 to 4°C.

Figure 32 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 32). 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.

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 33.

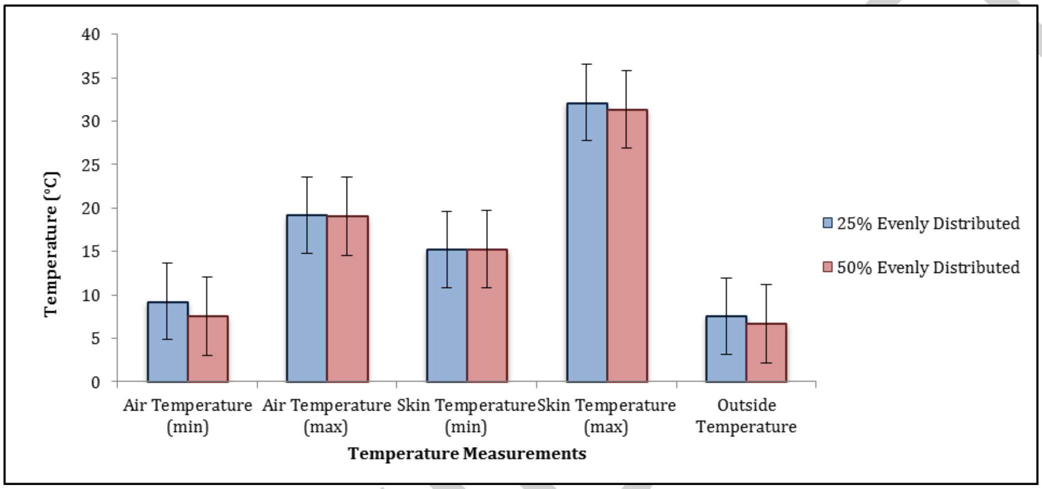

Figure 33. Effects of additional boarding beyond TQA guidelines (50% versus 25% for outside temperatures of 40-49°F, 4-9°C, n=3) on minimum and maximum zone-centered air temperature and minimum and maximum skin temperatures.

Figure 33 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 6. For outside temperature ranging from 20 to 49°F (-7 to 9°C), the majority of transport internal thermal environment stayed within cool condition ($32 < T_{in} < 65$°F; $0 < T_{in} < 18$°C) and only a small duration of the transport (0.2% to 10.2%) encountered cold condition ($5 < T_{in} < 32$°F; -15°C $< T_{in} < 0$°C).

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.

Implications (Industry-Focused)

Forty-three monitoring trips were completed to assess the thermal micro-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 collected 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.

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 (7 to 100°F; -14 to 38°C). With trailer management corresponding to TQA guidelines for bedding, boarding, and misting, 43 monitoring trips were completed from May 2012 to February 2013. The trailer was managed by the cooperating driver 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 monitoring trips observed road-transport duration ranging from 0.2 h to 1.5 h for before transport period, 0.8 h to 4.2 h for during transport period, and 0.1 h to 1.9 h for after transport period.

Results revealed that for current TQA recommendations, extreme and potentially detrimental thermal conditions were observed within the trailer for outside temperature below 20°F (-7°C) and above 90°F (32°C). The duration of the extreme cold events were limited (0.1 to 3.4% of the observations during trips observing T_{in}<5°F, -15°C), but the extreme hot was a larger portion of the trip (19.3 to 68.5% of the observations during trips observing T_{in}>95°F, 35°C). Emergency Livestock Weather Safety Index was observed on the trailer when outside temperature was above 10°C (0.1 to 63.7% of observations with Emergency conditions) despite having much less occurrence of corresponding extreme hot temperature inside the trailer.

The 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 skin temperature was separated out by other weather conditions and boarding percentages. These results highlight the potential micro-environmental challenges encountered with thermal extremes within the trailer and the need to achieve more thermal uniformity throughout the trailer.

Animations representing the temporal-spatial thermal conditions were created to visualize extreme conditions for location and severity over the course of the trips. These animations were compared to the comparisons of the summary variables for consistency.

Assessment of TQA Bedding Recommendations. Based on the results of this study, bedding

did not appear to offer thermally insulative benefit to the pigs in cold weather. In the coldest temperatures, freezing temperatures were observed at floor level prior to loading pigs, indicating that pigs were likely loaded onto freezing floors and 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. From a thermal consideration, a minimum level of bedding is beneficial to limit skin contact with floor material.

Frozen bedding and floor temperatures were observed at the start of and into the transport period for some monitoring trips. Heavy bedding during winter has the potential to increase the thermal mass that the pigs must overcome, essentially a larger quantity of cold and potentially frozen bedding and thus longer duration of freezing floor conditions. Frozen bedding was visually documented for several trips. Reducing moisture in the bedding could reduce the severity of this challenge, though pigs contribute a substantial amount of moisture to the environment.

One challenge for interpreting the TQA guidelines for bedding results from interpreting the bedding quantity to apply. If the categories for light, medium, and heavy boarding are not eliminated from the revised TQA, definitions of the beddings levels should be revised to account for variations in bag/bale sizes, pack compactions, moisture content, and substrate type. For example, a performance-based description of coverage amount (or photos demonstrating coverage) at each level would be more useful than number of bags/bales.

Assessment of TQA Boarding Recommendations. Based on the results of this study, the current recommendations for boarding are appropriate and may be further simplified to allow flexibility to the driver. Altered boarding distribution showed potential for manipulating ventilation patterns and potentially creating a more uniform thermal distribution within the trailer.

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.

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 20 to 40°F (-7 to 4°C), 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 40 to 49°F (4-9°C), 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.

Temperature distribution patterns generalized in this study did not consistently follow the expected trend for inlets at the rear and exhaust at the front of the trailer. Combined with the temperature distribution analysis, these results support the suggestion that ventilation patterns within the trailer and the exhaust was commonly occurring at the rear of the trailer. 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.

Assessment of TQA Misting Recommendations. Based on the results of this study, misting recommendation in the 50-69°F (10-20°C) range should be removed. Additionally, the implementation of misting and fans must be applied for all areas of the trailer for a benefit to be realized for all pigs. Further research is needed to make more detailed recommendations for misting.

Observations within the trailer for outside temperature ranging from 50-69°F (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 misting in this temperature range because the thermal conditions are acceptable without it, and misting might result in chilled pigs.

Two approaches for application of misting prior to transport were observed. The best-case scenario for misting during loading was very similar to the best-case scenario of misting after loading, though additional cooling of the air was recorded for misting during loading. Evidence from the animations also showed that misting while loading yielded a reduction in air temperature covering a much greater area of the trailer. The effectiveness of misting is critically impacted by the location and direction of the misting nozzles such that the coverage area is maximized and all pigs are sprayed. In this observational study, nozzles were arranged to cover the length of the trailer but insufficiently covered the width. The distribution and locations of misting nozzles inside the trailer is critical for improving the thermal uniformity of cooling effects throughout the trailer.

The cooling observed for the misting prior to transport in this study was not likely to be pig surface cooling, but instead air cooling. Considerations for the two options for cooling with application of water are quite different for optimal cooling. For pig surface cooling, intermittent wetting and constant air velocity are essential, and evaporation of the water provides the cooling to the pig surface. For air cooling, a fine mist or fog alters the air properties such that the air temperature is reduced, which consequentially also increases the relative humidity.

The difference between the options for cooling with application of water is not apparent in TQA, and the critical factors for the effectiveness of using water to cool were not thoroughly explored in this limited study. One recommendation is to further explore the different methods for water application and provide specific TQA guidelines for each. For example, optimal conditions for water temperature, water pressure, application duration, and air velocity vary depending on whether the approach is fogging, misting, or spraying, and also vary with the outdoor conditions.

Fans located externally (with or without misting inside) to 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, but was not uniform throughout the trailer. Cooling effectiveness 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 our scenario, and limited or no cooling was observed for the upper level of the trailer.

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 should be considered in further, more detailed, research.

Other Suggestions and Observations.

Stopping during transport. Based on observations during monitoring trips, stopping for breaks resulted in rapid temperature increases on the trailer (5-7°F, 3-4°C 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.

Need for a Weather Safety Index applicable to pigs. One limitation of the data summary in any pig micro-environmental assessment results from the lack of verified method to bring together measures of air temperature, humidity, air velocity, solar radiation, etc. in a quantitative measure reflective of pig thermoregulatory response. In this study, we applied the Livestock Weather Safety Index, but the categories of this index were created for beef cattle in a production setting using only air temperature and relative humidity. This is likely not reflective of pig responses during transport. A similar set of categories should be developed for pigs, and should include additional measures highly relevant to pigs, specifically air velocity.

Need for thermal uniformity within the Trailer. Analyses in this study considered average, best, and worst-case scenarios under extreme conditions. The rationale for this consideration was that the best-case scenario demonstrated the potential for the approach to work, and the worst-case scenario represented the reality of the pig in the most extreme situation which would be the most thermally challenged pig. This study did not thoroughly examine alternative strategies to alleviate these extremes, but we recommend further exploration into alternative management strategies that could create more thermal uniformity and reduce the span of conditions between best and worst cases, especially during extreme weather conditions.

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