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Evaluating Thermal Comfort of Broiler Chickens during Transportation using Heat Index and Simulated Electronic Chickens

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science in Biological Engineering

by

Kaushik Luthra
Govind Ballabh Pant University of Agriculture and Technology, Pantnagar
Bachelor of Technology in Agricultural Engineering, 2015

August 2017
University of Arkansas

This thesis is approved for recommendation to the Graduate Council.

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Abstract

Broilers experience high physiological stress during pre-slaughter transport, especially under extremes of thermal environment. Characterization of thermal environment on the trailer is crucial to identify stress-prone regions during transportation. At the same time, quantification of heat loss of the broilers loaded on trailers is important in understanding the well-being of the broilers. We have developed four electronic chickens (E-chickens) to simulate the sensible heat loss of live broiler during transit and holding period in commercial live-haul trips. It is an average broiler-sized enclosure with a thermostatically controlled circuit to keep the internal temperature at 41°C. Power consumption as a result of four different combinations of covering the enclosure as well as their sensitivity with exposed wind were compared. Double layer of fleece fabric was selected as the insulation cover for the E-chickens to match the sensible heat production reported in literature. Heat loss exhibited a positive correlation with the wind and a negative correlation with the temperature gradient between internal and external environment. However, the wet cover of E-chickens did not increase heat loss compared to dry cover, indicating its inability to release moisture unlike evaporation from natural feathers and respiratory water loss. Thirty-two commercial live-haul trips were monitored to determine humidity ratio increase-above-ambient air humidity, E-chickens were installed in eight of the trips. Moderate levels of measured power consumption of the E-chickens suggested that ambient temperatures in the range of 11°C-25.1°C (during transit) and 5.3°C-21.7°C (during holding) were in the zone of thermal comfort (allowing the live chickens to regulate heat by their metabolism to stay comfortable). For the holding period, the winter trips were mostly in the zone of thermal comfort, but during summers, hyperthermic conditions were widespread during transit. Fan-assisted evaporative cooling during on-farm loading may have introduced additional

cooling due to wetting of live chicken surface, not quantified by the limitation of E-chickens.

The mild weather observed during spring and fall season was the most comfortable for broilers.

Acknowledgements

First and foremost, I would like to thank God Almighty for guiding me and giving me the strength to be able to work on my research. I highly appreciate my advisor Dr. Yi Liang for the tireless work she put in this thesis and always believing and backing my skills. I am grateful to the funding agencies, U.S. Poultry & Egg Association and University of Arkansas Division of Agriculture for providing funds for this research. All the integrators that provided resources for us to take the field data are highly appreciated. I especially thank Drs. Thomas A. Costello and Susan E. Watkins for their guidance and support they provided throughout the research. My acknowledgments extend to Drs. Edward Gbur and Andy Mauromoustakos for their statistical input and advice during the data analysis. I would like to appreciate graduate students Douglas Aldridge and Christian Heymsfield for their sincere efforts in carrying out the data collection processes and also providing essential participation in the experimental design. The entire Biological and Agricultural Engineering fraternity with particular thanks to Randy Andress and Linda Pate.

The most critical support came from, my loving wife Akshita Mishra, for her moral support, strength, and encouragement. I would like to remember my beloved late father, Anupam Luthra who always kept his trust and encouraged me to follow my dreams. The work could not have been accomplished without continuous encouragement and support of my mother, Swati Luthra Gogna and my step-father, Prem Chand Gogna. Not to forget all my friends in Fayetteville and India who stood by me at my low times and shared my happiness with me whenever I reached out to them.

Dedication

This thesis is dedicated to my wife Akshita Mishra for her belief in me even when I did not believe in myself. My late beloved father, Anupam Luthra who was always there in my memories and inspired me to work hard for building my life. My will and self-belief to fight all the odds and work to build my dreams led me to carry out my work passionately.

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List of Abbreviations

Boarded-Double	BD
Boarded-Single	BS
Boarded-Wrapped	BW
Dead on Arrivals	DOA
Humidity Ratio	HR
Open-No Water	ONW
Open-Water	OW
Relative Humidity	RH

1. Introduction

1.1 Current U.S. broiler industry

Every year, approximately nine billion broilers are grown commercially in the United States with around 40,260 million pounds production of chicken (fig. 1.1). Chicken is the most consumed meat in the United States, with 91 pounds per capita annual chicken consumption in 2016 (fig. 1.1). The U.S. broiler industry is not only the largest producer in the world but also the largest exporter of chicken. Around 16.5% of the total production is exported annually (USDA, 2016). Georgia, Arkansas, and Alabama are the top three chicken producing states in the U.S. (USDA, 2016).

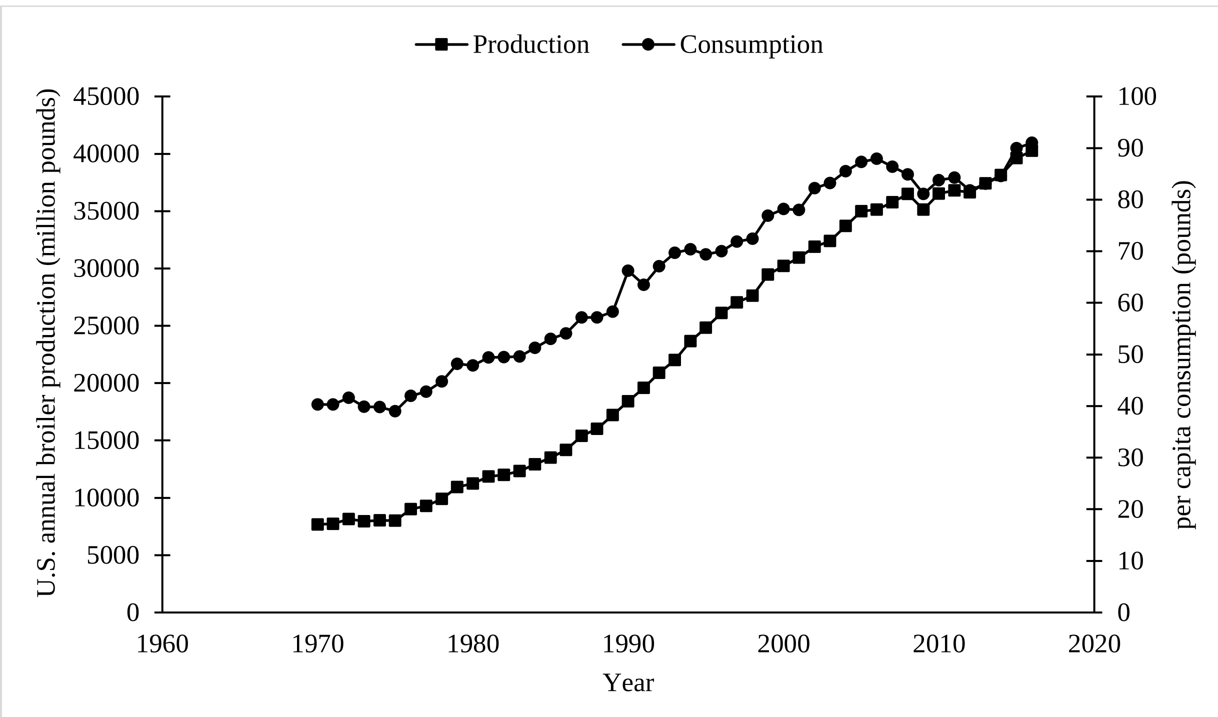


Figure 1.1 U.S. annual broiler production and per capita consumption of chicken in pounds from 1970 – 2016 (based on USDA data, retrieved from www.nationalchickencouncil.org).

Approximately 40 companies are working in the poultry industry on a "vertically integrated" basis – most of the production and processing of chicken are directly controlled or supervised by the companies. About 29,500 family farmers work under contract with the companies as a part of the vertical integration. Approximately 95% of broiler chickens are raised on these family farms, while the remaining 5% of the production takes place in the company-owned farms (USDA, 2016).

1.2 Pre-slaughter broiler transport

As the broilers reach the target body weights for the market, they are moved to the centralized processing plant for slaughter and processing. Pre-slaughter typically includes catching broilers at the farm, handling, loading on trailers, transportation and unloading at the processing plant for slaughter. At the farm, chickens are caught either manually or mechanically and load onto cages (referred to modules) (Bayliss and Hinton, 1990; Mitchell and Kettlewell, 1993). The fork-lift is used to load or unload the modules. The catching crew loads around 500 to 1500 broilers per person-hour (Nicol and Scott, 1990). Our data indicate that within 3.5 min on reaching the plant, broilers are held in the modules in the holding shed before they are slaughtered. Holding sheds are mostly open structures with metal roofs and open sides with mechanical ventilation equipment, although the size of sheds, the number, and type of fans, or the operating procedure of fans vary by company and location.

1.3 Current trailer and module design

Broiler chickens are transported by a 14 m long solid-floor trailer with modules stacked 2.4 m wide and 2.5 m high (fig. 1.2). There are 22 modules stacked as 11 stacks of top and bottom pairs, although fewer modules can be used to increase the spacing between these stacks for better air flow in summers.

Figure 1.2: Transportation trailer used for broiler transport in the Southern U.S.

Each module consisted of 10 perforated compartments that are arranged vertically as two columns side-by-side (fig. 1.3). In each compartment there is a hinged metal door for loading and unloading of birds, a solid plastic floor provides a firm base inside the module for chickens to rest during transport. The module is 2.4 m in length, 1.2 m wide and 1.2 m high. There is typically 15 cm gap in between the stacks which facilitate loading and unloading and also improves air movement through the modules. The side and the back of the module are made of metal wires with large openings, while the top of the module has a thin metal roof. In winter, plastic boards (refers to “wind boards”) are screwed onto the sides of the modules to protect the chickens from the elements. The number of these wind boards is decided based on the severity of the weather. Also, the modules are wrapped with plastic wrap during the actual transport when the ambient temperature is near the freezing point. This wrapping is removed at the holding shed by one of the employers to comfort the broilers in a warmer environment developed by the heating elements under the shed. On the other hand, in summers most of the trips had no tailboards and wind boards on the modules. And, at extremely high temperatures, water sprayer, and fan misters were used during loading and holding period. The stocking density of the chickens ranges from 20 – 25 birds per compartment and is decided by the live-haul personnel on duty based on the weather.

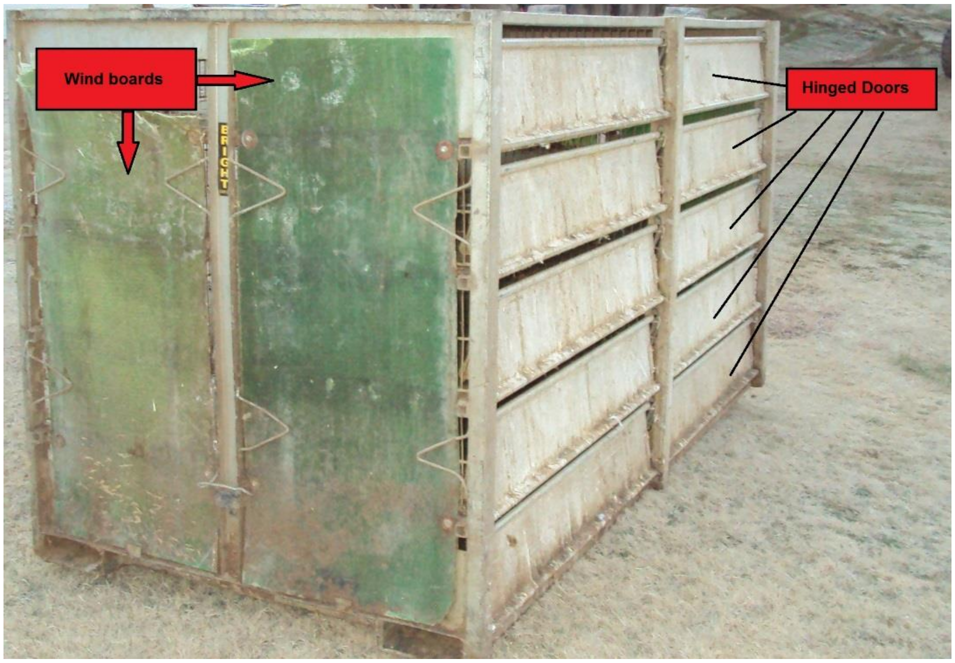


Figure 1.3: Steel module with ten compartments, two plastic wind boards at each side.

1.4 Homeostasis of broilers

The relation between the physiological interactions of broilers and its thermal environment is complex but its understanding is of utmost importance for the better production and management of the birds. Research has been done to better understand the relationship between the thermal environment and broiler thermoregulation (Pereira and Naas, 2008; Simmons et al., 1997; Yahav et al., 2004, 2005). But few practical management issues have been resolved on the basis of these studies; this sheds light on the limited knowledge transfer to the people in the industry (DeShazer et al., 2009).

Broilers are homeothermic endotherms who attempt to keep their body temperature steady. The physiological and behavioral controls of these homeotherms strive to maintain their body temperature near 41°C by continuously controlling the thermal energy balance, i.e. heat generated through metabolism must equal heat loss to the environment (sensible and latent heat loss). This physiological control for maintaining the internal body temperature is knowns as homeostasis. Homeostasis can be disrupted by extreme environmental conditions like heat and cold stress which require various responses by the broilers to regain homeostasis (Curtis, 1983; Willmer et al., 2009).

Broilers dissipate heat by four different mechanisms: conduction, convection, radiation and evaporation (DeShazer et al., 2009). Sensible heat loss which comprises the first three heat loss mechanisms and is driven by the thermal gradient between the broiler near ambient air, nearby radiative surfaces and the internal body temperature. On the other hand, the vapor pressure gradient drives evaporative heat loss which is also known as latent heat loss. As the ambient temperature is elevated to near the body temperature of the broiler, evaporation becomes the major heat loss mechanism. Due to the lack of sweat glands broilers are unable to lose heat through skin surface evaporation. Heat loss through evaporation takes place from the respiratory tracts of broilers, which may not be sufficient to tackle the increasing body temperature during extreme summer conditions. For a better understanding of how the homeostasis is maintained, we need to understand the behavior of broilers under the different zone of thermoregulation which is as described in the following discussion.

Broilers have three zones of the thermoregulatory response, i.e. zone of least thermoregulatory effort, the zone of metabolic regulation and, the zone of latent heat loss control (DeShazer, 2009). In the zone of least thermoregulatory effort, the ambient temperature is in the thermoneutral zone for the broilers i.e. 23°C to 29°C (Meltzer, 1983) or 18°C to 30°C (Pereira and Naas, 2008). The broiler body temperature is maintained near 41°C without changes to normal metabolism and behavior (Kettlewell and Moran, 1992). In the zone of metabolic regulation, the ambient temperature is below the lower threshold of the thermoneutral zone where additional heat generation is required. Due to a withdrawal of feed and water before loading for transport to slaughtering facilities (Dadgar et al., 2010), broilers depend on shivering to increase their heat generation. However, broilers also try to keep themselves warm by huddling together with other birds on the modules and by fluffing their feather to add an extra layer of insulation. Alternately, at high ambient temperatures, in the zone of latent heat loss control (when the ambient temperature is above the upper threshold of the thermoneutral zone) broilers try to stay away from other birds with similar surface temperature. However, due to the space restriction on the modules, broilers cannot avoid being concentrated in the space with other birds.Under these heat stressoocnditions, broilers resort to increased respiratory evaporative heat loss by panting (increasing the volumetric respiratory exchange) given that sensible heat loss is diminished (minimum when the air temperature is near to 41°C). Evaporative heat loss can prove lethal when the difference between the ambient temperature and body temperature approaches zero (Simmons et al., 1997), dehydration (depleting the body water resource) and disruption of the blood acid-base balance occurs which leads to more metabolic heat production (DeShazer, 2009; Geraert et al., 1996). Also, panting as a mechanism to reduce the body temperature has higher energy input in maintenance than the sensible heat loss (Yahav et al., 2005).

1.5 Characterization of thermal environment using thermal indices

The thermal regulations of animals are influenced by environmental factors such as air temperature, relative humidity, air velocity, air vapor pressure, the thermal resistance of the surroundings, the heat capacity of contact materials, etc. (Eigenberg et al., 2009; Hahn, 1976).

Trailer design affecting airflow patterns and crowding is also crucial for heat transfer and the thermal comfort of the animals (Eigenberg et al., 2009). Air temperature is the most convenient measure for assessment of thermal conditions. Hahn (1976) indicated that air temperature which is important to measure the convective heat loss could be affected by the other environmental parameters. Therefore, it is necessary to measure other environmental parameters like relative humidity and air velocity for more accurate description of the thermal environment (Cox, 1997; Hahn, 1985; Eigenberg et al., 2008). Air velocity influences the convective heat loss of the animals when the ambient temperature is below the core body temperature, and by increasing the air flow, the negative impacts of the hot weather can be reduced (Curtis, 1983; Eigenberg et al., 2009). Relative humidity is also another factor that needs to be managed for the mitigation of the effects of extreme weather (Cox, 1997). Uncomfortable levels of relative humidity decrease respiratory evaporative cooling and can severely dent the well-being of the animals and increase the mortality and the occurrence of diseases (Lowen et al., 2007).

Thermal stress experienced by the broilers during the transport is a major concern of the broiler industry (Kettlewell, 1989; Mitchell and Kettlewell, 1993; Webster et al., 1993). Especially, heat stress is the most dangerous factor that leads to high mortality in summers in the Southern U.S. (Vecerek et al., 2006). Heat stress indices provide a convenient way to assess the potential heat stress level on the broilers. In hot weather conditions, high ambient temperature, high solar radiations, and high relative humidity are the main environmental stressors that impart heat stress on broilers in transit (Finch, 1984). A heat index can be simple dry bulb temperature scale or a combination of all the factors that provide the weighted estimation based on the factors considered. At first, it is crucial to understand the behavior of particular breed and species of broiler under various external conditions which can impart heat stress. To understand their behavior, one would need to monitor physiological parameters such as core body temperature, heart rate, feed intake, heat loss, etc. Plotting the values of these parameters against the possible stressor such as external temperature and humidity gives us an idea of how the broiler is responding to various stressor values. Thus, identifying a sudden change in some physiological parameters which delineate certain critical values from the rest.

A heat index known as temperature humidity index (THI) is highly used and has been developed for various farm animals. It is a combination of dry and wet bulb temperature and was represented by the following equation for broilers (Tao and Xin, 2003),

$$THI = 0.85 * T_{db} + 0.15 * T_{wb} \quad (1)$$

where,

T_{db} = dry bulb temperature (°C), and

T_{wb} = wet bulb temperature (°C) at a particular time.

Another index, known as apparent equivalent temperature (AET), was used as an index of the thermal load during transportation of broilers for physiological response modeling (Mitchell and Kettlewell, 1998, 2009). AET was calculated from dry bulb temperature, water vapor pressure and the psychrometric constant. It can also be calculated using dry bulb temperature and relative humidity alone as defined in the equation below (Mitchell and Kettlewell, 1998).

$$AET = T_{db} + \frac{10^{\left(31.5905 - 8.2 * Log10(T_{db}+273) + 0.0024804 * (T_{db}+273) - \frac{3142.31}{(T_{db}+273)}\right)} * \Phi}{0.93 * (0.0006363601 * (T_{db}+273) + 0.472)} \quad (2)$$

where,

Φ = observed relative humidity (RH, expressed as a decimal).

Using AET approach, combinations of T and RH that produce the equivalent biological effects on the broilers based on physiological response modeling were determined by Mitchell and Kettlewell (1998; fig. 1.4).

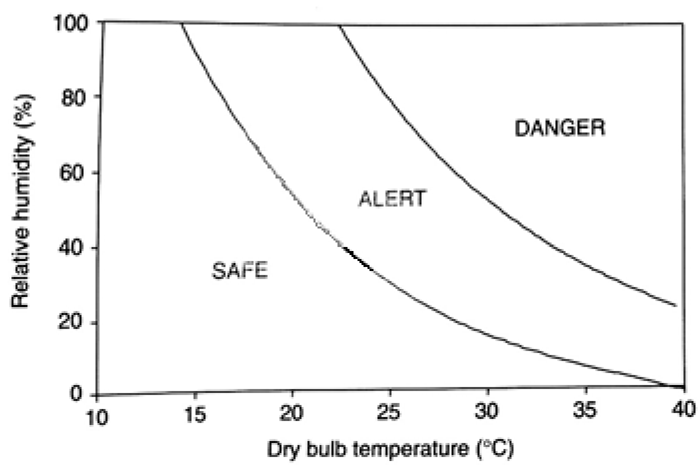


Figure 1.4: Thermal comfort zones for broiler transport (Mitchell and Kettlewell, 1998; Safe limit, AET=40°C; alert limit, AET=65°C).

Both of the above two indexes describe the relation of temperature and humidity on physiological responses of broilers, but they do not incorporate the effect of wind velocity, which is important to consider in an environment with the substantial wind, such as transport trailers moving on the highway or receiving forced airflow while in holding sheds. Thus, it is crucial to include wind velocity as a thermal parameter in finding the heat index. Temperature-Humidity-Velocity Index (THVI) includes velocity as one of the factors for the calculation of index; Tao and Xin (2003) defined the THVI equation as follows:

$$THVI = THI * V^{-0.058} \quad (3)$$

where,

V = wind velocity (m/s; $0.2 < V < 1.2$).

Tao and Xin (2003) defined normal, alert, danger, and emergency regions of homeostasis for the broilers (fig. 1.5). The core body temperature increase of 1°C, 2.5°C, and 4°C was correlated with the exposure time at the respective THVI required by the broilers to reach that amount of increase in body temperature.

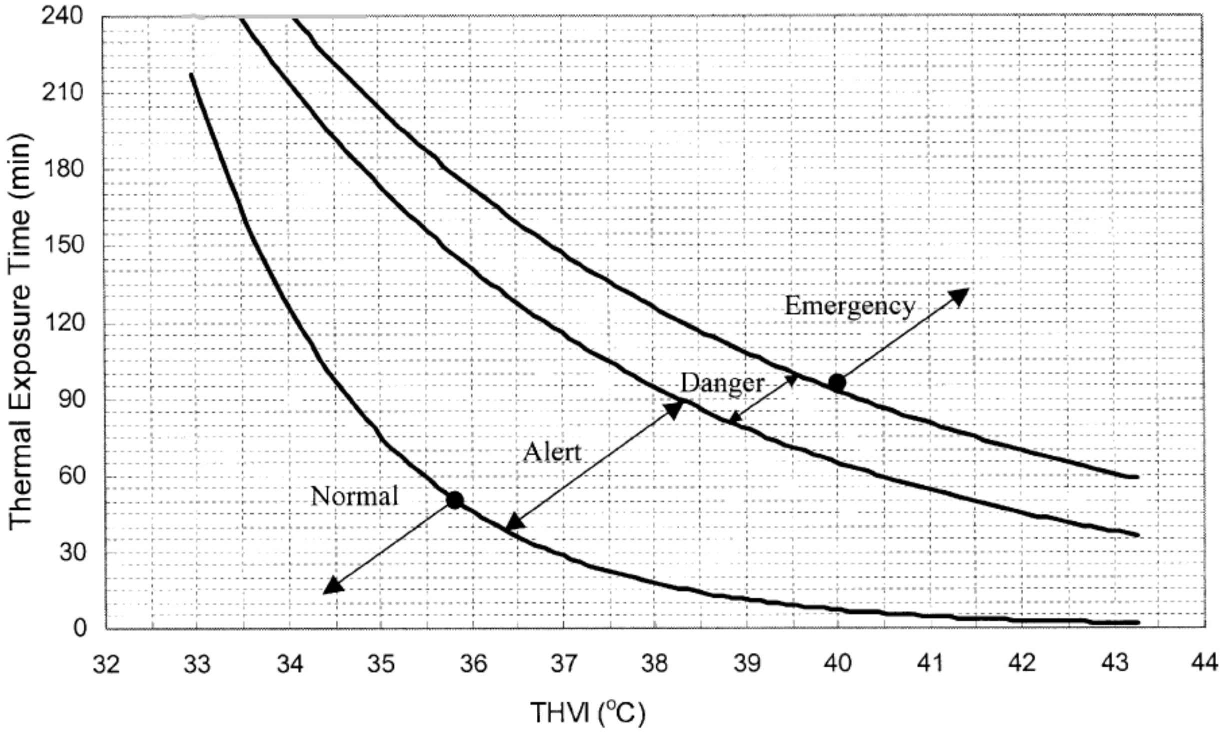


Figure 1.5: Normal, alert, danger and emergency regions of homeostasis on THVI scale with relation to the exposure time (Tao and Xin, 2003).

1.6 Problems of well-being of broilers during pre-slaughter transport

Environment control of poultry production houses has been studied extensively to gain production efficiency over the years, yet not very many studies are done to improve environmental conditions during the pre-slaughter broiler transport. During transportation, broilers are subjected to different stressors such as vibration, acceleration, withdrawal of food and water, commotion effects, and extremes of complex thermal micro-environment (Abeyesinghe, 2001; Carlisle, 1998; Kettlewell et al., 1994; Mitchell and Kettlewell, 1998, 2009;

Nicol and Scott, 1990). Some of these stressors are related to the anxiety that the broilers experience amid transport. Temperature extremes have been identified as the most significant stressor, with heat stress representing an enormous risk to the broilers on board (Mitchell and Kettlewell, 1994, 1998; Weeks and Nicol, 2000). Some of the broilers die during the course of transportation and these deaths are referred as “dead on arrivals” (DOA). Both the heat and cold stress have been found to affect meat quality (Dadgar et al., 2010; Mitchell and Kettlewell, 2009) and increasing DOA (Hunter et al., 1999; Nijdam et al., 2004; Vecerek et al., 2006). Bayliss and Hinton (1990) estimated that 25% of DOA was due to pathological lesions, 35% due to catching and handling while loading and unloading, and 40 % of these DOA was attributed to thermal stress and suffocation experienced on the transport trucks. Broiler DOA in the U.S. ranges from 0.35% to 0.37% (Agriculture Statistics, Inc. cited by Ritz et al., 2005). Average estimations of DOA in summers may go up to 0.46% (Nijdam et al., 2004), representing not only an economic loss to the poultry industry but also indicating reduced animal well-being for all the birds exposed to the heat stress conditions.

Past research in the United Kingdom characterized the thermal environment experienced by broilers during transport. These studies suggested that the distribution of dead broilers is not random, and indicates the existence of a variable thermal load and a thermal core inside the modules (Kettlewell et al., 1993; Mitchell et al., 1990; Mitchell and Carlisle, 1992; Mitchell and Kettlewell, 1993). It also confirms the variation of ventilation and regions of discomfort on the modules loaded on trailers. Past studies (Hoxey et al., 1996; Mitchell and Kettlewell, 2009) proposed that the physiological stress could be minimized by maintaining the air temperature and humidity within the broiler’s thermoneutral zone, by controlling the air movement inside the modules during transport and also in holding sheds. Natural or passive ventilation is common on trailers in the U.S. However, this kind of ventilation is highly variable and dependent mainly on truck movement, the temperature gradient between ambient and internal environment, and wind speed and direction. Not much control can be achieved by the air movement, except for the application of wind boards (Mitchell and Kettlewell, 2009). A study (Hoxey et al., 1996) described the ventilation pattern of the truck in motion, which tells that the pressure distribution is such that air flows within the modules on the trailer from the back to the front. The uncertainty in ventilation relates to the variable speed of the truck and no clear inlet and outlet of air on an open trailer, which makes characterizing wind speed on the live-haul trailer difficult. Hunter et al. (1999) suggested that wetting of broilers occur in modules near ventilation inlets during the wet weather due to the aerosolized road spray. The combination of low temperature and wetting can prove fatal for the broilers as wetness disrupts the feather insulation, and the broiler can suffer hypothermia.

Freeman et al. (1984) studied the effect of long distance transportation of 2 to 4 hours and concluded that the stress increases with the distance of travel. Studies also reported that about 0.1 % more DOA was recorded in summer as compared to winter (Bedanova et al., 2007; Warriss et al., 2005). The time of day plays the key role in the variations in DOA. Death loss of broilers was highest in the afternoon as compared to nights (Bayliss, 1986) in summers. Therefore, it is advisable to make live haul trips at other time of the day in summers, keeping the number of trips to the minimum during afternoons. However, to implement the suggestion, sufficiently larger holding shed capacity with proper cooling would be required to provide for continuous operation of the plant while avoiding transport during the hottest part of the day.

Webster et al. (1993) used the electronic chickens to measure the heat loss of average-sized broilers during cold weather transportation in England. Quantifying heat loss of the broilers loaded on trailers for transport from farms to plants is challenging but important in understanding the wellbeing of the broilers during the live-haul process. The electronic chicken was an average broiler-sized enclosure with a controlled power source to maintain the internal temperature at a set point. He reported the difference in heat loss and the thermal loading on trailers with or without the use of curtains. Weeks et al. (1997) simulated sensible heat loss of pullets and laying hens using E-chickens in transit. Different trailer designs with natural and artificial ventilation were compared based on the data obtained from loads during winter and summer.

Weather in the Southern United States is different from the United Kingdoms. Also different are the physical configuration of live-haul trailers and modules and live-haul procedures, including the module materials, gaps between rows, control measures (curtains and wind boards), trip lengths, broiler size and seasonal stocking density. Research data are severely lacking on the transport of farm animals in the U.S. (Ritz et al., 2005; Xiong et al., 2015), but are much needed to identify any well-being deficiency in current practices. Characterizing thermal environment during live haul process in U.S. is a logical first step towards improving poultry production and animal well-being.

2. Objectives

Overall, the study is conducted to characterize the spatial variability of the thermal micro-environment on commercial broiler live-haul trailers during pre-slaughter transport in each season of the year in the Southern U.S. Also, high thermally stressed regions are identified by quantifying the heat exchange of broiler chickens within the trailers. For this thesis, two objectives address characterization of the broilers during transport and identify the regions that are thermally stressful to birds.

1. Characterization of the increases in humidity within broiler live-haul trailers during transportation under different climate conditions in the Southern U.S.

2. Development and testing of highly portable electronic chickens (E-chickens) with easy installation, including the evaluation of its performance in measuring the sensible heat loss under different climate conditions, thus to identify any condition that leads to excessive or insufficient heat loss.

3. Materials and Methods

3.1 Commercial live-haul monitoring for moisture load characterization

Thirty-two broiler live haul commercial trips were monitored during transit and holding period to record basic thermal parameters such as temperature, humidity, and the wind. Data covered all seasons typical in the Southern U.S. and different management practices that were used for mitigation of extremes of climate on birds. All methods used in the research were approved by University of Arkansas, Institutional Animal Care and Use Committee (IACUC No. 15026). Data reported depicting the overall thermal condition variations on the commercial live haul trailer during various seasons and locations on trailers.

3.1.1 Field data collection and trip categorization

Before every trip we coordinated with the personnel of the poultry integrator (or company) and all the necessary information was exchanged to plan the data collection process. Based on the target ambient conditions, the trips were selected to record the ambient data on the trailers. The dry bulb temperature and relative humidity were measured using small portable temperature/humidity data loggers (Hobo U23 Pro v2, -40°C to 70°C, ±0.2°C and 0 to 100% RH, ±2.5%, Onset Computer Corporation, Bourne, MA; fig. 3.1 B; iButton DS1922L, ±0.0624°C, Maxim Integrated, San Jose, CA; fig. 3.1 A) which recorded the dry bulb temperature. The data loggers were launched in the laboratory to record at an interval of 30 seconds after a specified time. Installation of the thermal loggers was done using plastic zip ties at the plant before the truck left for the farm. Thermochron data loggers were covered with plastic wire mesh sleeve to restrict the loggers from falling out of the trailer. The location of processing plants and farms, the time of departure and arrival, transit and holding period, management practices used at the farm and plant, any stops during the transport and the location of data loggers were noted on field note recording sheets. Management practices, i.e. ambient conditions, stocking density and any other practices of broiler live haul, were neither controlled nor modified in any manner for this research. All the practices were decided by the company personnel through their experience and protocols. Anemometers (Kestrel 4500; ± 0.1 m/s from 0.4 to 40 m/s; Kestrelmeters.com Minneapolis, MN) (fig. 3.1 C) were installed on the trailer at the farm just before the loading started due to their limited digital data memories. These anemometers measured the wind speed at six pre-determined location inside the trailer, including both interior and exterior. Initially, we did not use the wind sensors until we realized the need to measure the wind. The wind speed of the exterior and midline of the modules were recorded for few trips, and the distribution of wind sensors was variable due to the fewer loggers and initial adjustments. After the unloading of birds at the plant, all the loggers were recovered. Later, the loggers were cleaned, and the data were downloaded into a spreadsheet (Microsoft Office Excel, Microsoft Corporation, Redmond, WA).

A B C

Figure 3.1: Data loggers used to gather the environmental parameters (A) Thermochron data loggers-temperature (B) Hobo data loggers-temperature and humidity (C) Anemometer data loggers-wind speed.

The trips were categorized based on the five trailer configurations i.e. Open-Water (OW), Open-No Water (ONW), Boarded-Single (BS), Boarded-Double (BD), and, Boarded-Wrapped (BW). These configurations represented different management practices of the company to alter the environment of the modules based on weather conditions. Open-Water configuration is when the modules have no wind boards (fig. 3.2 A) with the use of fan-mister arrangement (fig. 3.2 B) and/or hand fogger at the farm and the holding shed. Open-No Water configuration is similar to the OW with no use of fan-mister and fogger. Boarded-Single (fig. 3.3 A) and BD (fig. 3.3 B) configuration corresponds to the single and double wind boards used on the modules during the winters and also have tailboards. Boarded-Wrapped configuration (fig. 3.3 C) is similar to the BD with the addition of plastic wrapping used to cover the modules after they were loaded. The plastic wrapping protects the birds from extreme low temperature and excessive wind; wrapping is removed as soon as the trailer is placed in the holding shed to avoid any perceived moisture build-up.

A **B**

Figure 3.2: (A) Fans with misters (not visible) are used along with the hand sprayer while loading during Open-Water trips. (B) Movable fan-mister arrangement used at farms during loading in Open-Water.

A B C

Figure 3.3: (A) Trailer with Boarded-Single configuration kept in the holding shed (B) Trailer with Boarded-Double configuration during winters (C) Trailer with Boarded-Wrapped configuration during extreme winters.

3.1.2 Trailer thermal data processing

Temperature and relative humidity plotted over time were reviewed. The data for first five minutes of truck's departure from farms were removed due to high environmental instability experienced inside the trailer. This also marks the start of the transit period for our data analysis which ends once the trailer reaches the processing plant. Holding period starts immediately when the truck is placed in the holding shed; ends when the trailer is moved into the plant for unloading. Ambient data of the day of monitoring were obtained from the nearest weather station of the processing plants (www.wunderground.com, San Francisco, CA). The recording interval of ambient data was 15 min, 30 min, and 60 min; the ambient data were then converted into 30 sec data interval to match the trailer thermal data interval as we intend to calculate the increase above ambient data.

Relative humidity depends on the temperature and water content of the air; hot air needs more amount of vapor to saturate as compared to the cold air for the same volume of air (Lide, 2005; Perry and Green, 1999). To overcome this dependence of relative humidity on temperature and to express the absolute moisture conditions of air on the trailers, humidity ratio (HR) was calculated as the ratio of the mass of water vapor per unit mass of dry air (Albright, 1990).

Relative humidity, dry bulb temperature, and dew point temperature were used to calculate the HR as per the conversion formula given in Albright (1990).

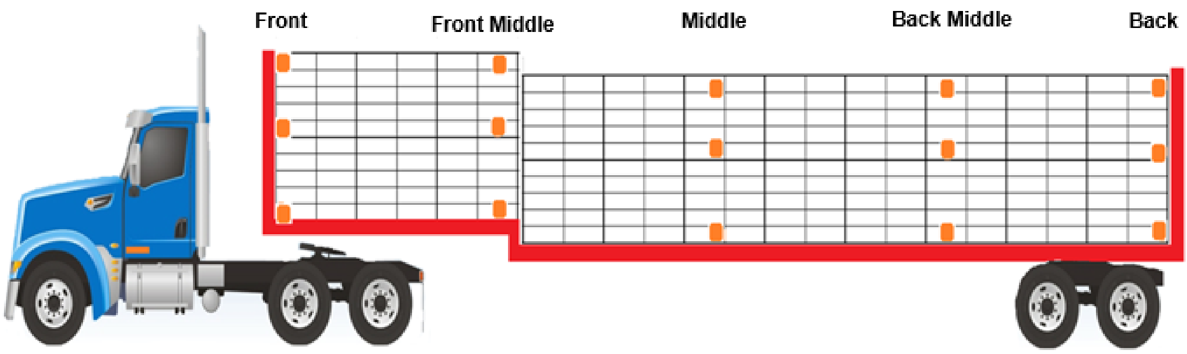


Figure 3.4: Data loggers' location on the trailers during commercial transportation.

After the conversion of temperature and relative humidity to HR, the mean of the HR of each logger location for transit and holding period respectively in every trip was obtained. To obtain a representation of moisture on the trailer, frequency graphs were plotted for trips in every ventilation configuration (OW, ONW, BS, BD, BW) during transit and holding period. Transit and holding period minimum, maximum and mean values of HR for each configuration were calculated along with the mean ambient values of HR. The humidity ratio increase-above-ambient for each logger was calculated by subtracting ambient values of humidity ratio from humidity ratio at each logger location. These increase-above-ambient values were grouped for transit and holding period based on ventilation configuration, exterior or midline location inside the module, trip number (1 to 32) and module row location on the trailer as shown in figure 3.4 to analyze the spatial variability on the trailer for various seasons. The mean HR increase-above-ambient value at each location averaged over all trips for respective ventilation configuration was used to obtain 3-D figures using MATLAB R2015a (The MathWorks Inc., Natick, MA) for visual comparisons between transit and holding period for each ventilation configurations (fig.

A.1−A.9). Since the wrapping was removed at the start of holding period in the wrapped trips, the BD and the BW configurations as in transit were merged to be considered as BD ventilation configuration for holding period analysis. Trips of duration less than 15 min were removed from the analysis of both transit and holding period. As a part of the larger study, the temperature values were also measured, and some temperature data (Liang et al., 2017) were used to interpret the HR results. Only the HR results are presented here.

An Open Water trip in June was selected to gather thermal data for heat index determination. The overall duration of the trip included 46 min of transit and 152 min of holding period. The mean ambient temperature was 33°C, with 55% relative humidity. The fan with misters was used during loading and also during the holding period to help keep the broilers cool. The temperature, humidity and wind data loggers were setup to measure the micro-environment of exterior and middle portion of the modules on five row locations along the length of the trailer (fig. 3.4). The objective was to find out the differences of the thermal environment due to the natural ventilation between exterior and middle of the modules. AET and THVI values combined for transit and holding at each exterior and midline location were calculated based on the eq. 2 and 3, respectively for the selected trip. Transit and holding period were combined for the calculation of the indexes so as to understand the effect of average ambient conditions found on trailers before slaughter on live chickens. Due to the applicable range for THVI calculation (Eq. 3), the wind speed used in the calculation was 1.2 m/s whenever the observed wind speed was above 1.2 m/s, and when the wind speed was lower than 0.2 m/s, 0.2 m/s was noted, as per the velocity range constraints expressed by Tao and Xin (2003).

3.1.3 Thermal data statistical analysis

The potential effects of various ventilation configurations, representing different management practices used in different seasons on the moisture load developed were represented by the relationship between variable HR increase-above-ambient, ventilation configuration, interior or exterior locations on the trailer and the row locations along the length of the trailer. Humidity ratio increase-above-ambient was the response variable for a three-factor analysis of variance model. Ventilation configuration, interior or exterior locations on the trailer, and the row location were the factors or the independent qualitative variables for the analysis. Different trips are treated as a random effect. Thus, the errors associated with the random variations between the trips, were considered in the analysis. Transit and holding period data were analyzed separately. The distribution of the data was checked for the assumption of normality of the distribution. The data were right skewed and seemed to follow a Chi-square distribution. The software SAS 9.4 (Cary, NC) was used for the analysis using the GLIMMIX procedure. The model for the analysis fits well into the category of generalized linear mixed model. Non-normal distribution of the response variable and the presence of a random effect are the conditions that fulfill the requirement of using the GLIMMIX procedure. Natural logarithm was used as the transformation function which connected the mean of the response variable (HR increase-above-ambient) to the parameter estimates of the three factors. Thereby, the transformed mean of the response ranged from $-\infty$ to $+\infty$, which was not present for the non-transformed response variable. Therefore, the link function formed a linear equation with the response and the parameter estimates and uses an iteratively weighted least squares method for maximum likelihood estimation of the parameters. Gamma distribution was used which is suitable for the data that are continuous, positive, right-skewed and the variance is near-constant with the natural logarithm link function. The type III tests of fixed effects on HR increase-above-ambient for the transit and holding period were conducted in SAS. Type III tests each factor's significance independent of other factors. Further, the least square means were analyzed to test any differences between the means of different levels of each factor and their interactions on HR increase-above-ambient measurements.

3.2 Electronic Chicken to quantify the live chicken heat loss

Different materials were used to insulate the E-chickens to try to match the published insulation value of a well-feathered broiler (0.3 °C m^2 W^{-1}; Webster et al., 1993). Average market broiler surface area was found to be 0.15 m^2 for a 5 – 6 lb. broiler and our E-chicken's surface area was similar (0.12 m^2). Four electronic chickens were developed, with their heat loss characteristic determined under lab conditions. They were installed in the modules along with the live chickens during the live-haul process in eight trips out of the total 32 that were monitored. The power consumption of these E-chickens varied with ambient conditions such as exposure to different temperature, wind speeds, and humidity.

3.2.1 Electronic Components and Control of Electronic Chicken

The hardware system of the E-chicken consisted of a microcontroller, input and output interfacing components, an electronic circuit with multiple power resistors (thin film power resistors, 12 Ω ±1%, 30 W), heat sinks, and a mixing fan to allow incremental stages of heating (fig. 3.5 (A)). The microcontroller ran a control algorithm to maintain the internal temperature of the box at a set-point (41˚C), with feedback controlled by two precision temperature IC sensors (LM34, Texas Instruments, Dallas TX) inside the box. The box was made of aluminum with a surface area of 0.12 m^2. The E-chicken was designed and fabricated by James Randall Andress, instrumentation engineer for the Biological & Agricultural Engineering Department under the guidance of Dr. Yi Liang, Associate Professor in the Biological & Agricultural Engineering Department.

Figure 3.5: Electronic chicken (A) without wrapping (B) with a double layer of fleece fabric wrapping.

A 12 volt, 3.4 amp-hour battery was used to power the system. A toggle switch was provided on the box for the operator to open or close the circuit. The voltage drop across a current sensing resistor (R_s, 0.02 Ω) was recorded by a voltage data logger (USB-503, 0-30 VDC, ±1%, Measurement Computing, Contoocook, NH). This voltage, when divided by the gain of the amplifier and resistance value of the sensing resistor, provided the current used by the heating elements at the time of measurement (fig. 3.6). A second data logger (USB-503, 0-30 VDC, ±1 %) recorded the voltage of the battery (V_{bat}). The product of the voltage and current yielded the power consumed by the E-chicken system at any time.

A proportional control algorithm cycled the heating elements in parallel (RT_1 to RT_4), one for each stage, as needed based on the difference between the measured and set point temperatures. Upon turning on the power switch, all four stages of heat cycled on. As temperature increased in the unit, stages four, three, two, and one sequentially cycled off as 88%, 92%, 96%, and 100% of the set-point are reached, respectively. In response to a drop in temperature corresponding to the same percentage of demand for heat, each stage cycled on. Should demand heat create a situation in which a stage was unable to reach the appropriate percentage of the set-point after the time that a stage had been on, the algorithm cycled on another stage. For example, should stage one increase internal temperature to 98% of the set-point, yet be unable to increase to 100%, stage two cycles on to assist, and so forth. The algorithm rotated which heating element was assigned to a control stage every 2 min to balance heat dissipation and workload by resistors.

The control algorithms and codings of each chicken were written using an Arduino microcontroller, with two IC temperature sensors as analog inputs, and executing on/off of each of the four parallel resistors based on the above control algorithm using digital output pins.

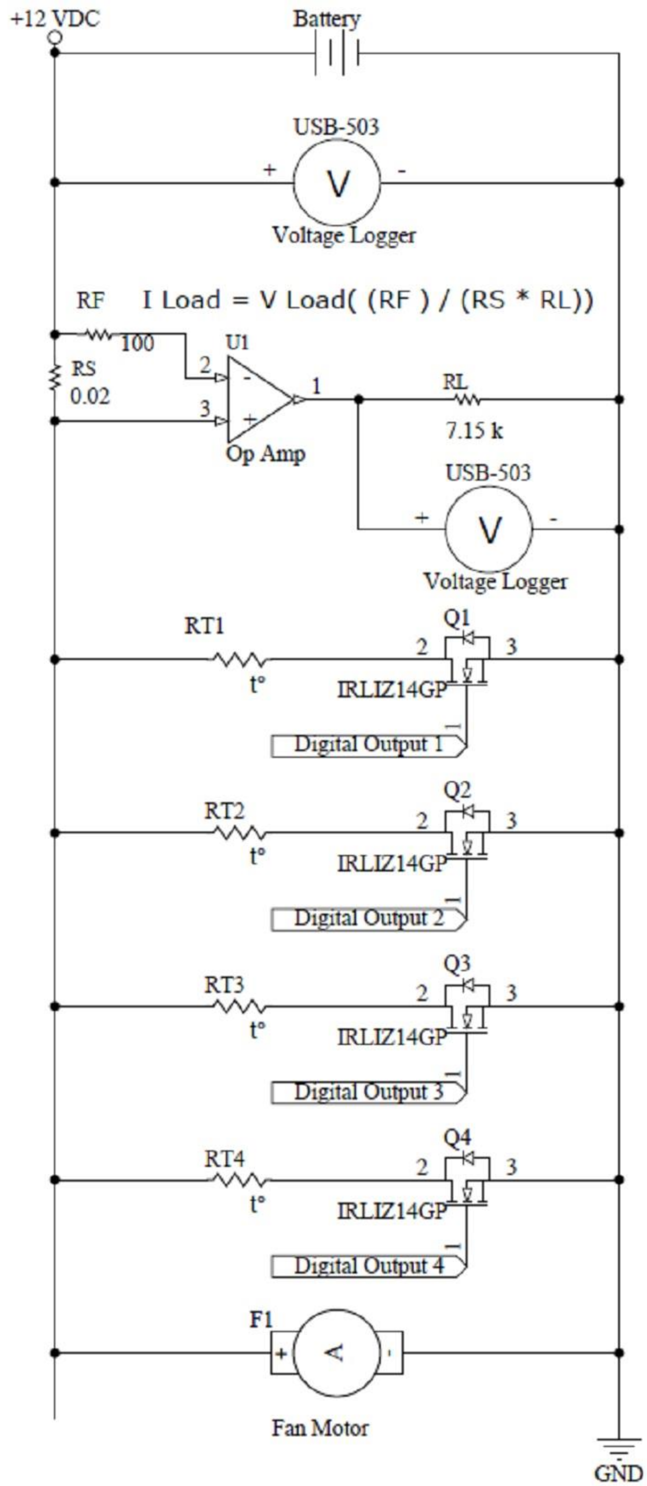


Figure 3.6: Schematic diagram of electronic chicken hardware showing major components including a battery, power resistors, battery voltage measurement and current measurements of the main circuit via a current sensing resistor (Andress, 2016).

3.2.2 Data Acquisition

Three thermochron loggers (fig. 3.1 A) were installed to record the internal temperature of the E-chickens at three locations for an average of T_b. Voltage and iButton loggers are time-synchronized and launched to record every 10 s. One thermochron logger kept six inches away from the enclosure was used to record ambient temperature, T_e. Heat loss at any time is calculated as in the equation below and averaged during a certain time of the trip. This allows the value of effective thermal resistance (R_{ch}) to be calculated. It is assumed that the power consumption rate of the electronic chicken to keep the body temperature constant at 41°C (106°F) is equivalent to the convective heat loss rate of the E-chicken enclosure (DeShazer, 2009).

The power consumption is calculated as follows:

$$P = V_{bat} * I = (A/R_{ch}) * (T_b - T_e) \quad (4)$$

Where,

P = power consumption (W),

V_{bat} = voltage measured in the circuit (V),

I = current measured in the main circuit via a current sensing resistor and an amplifier (A),

A = effective surface area of the electronic chicken i.e. 0.121 m^2 (1.3 ft^2),

R_{ch} = effective thermal resistance of animal between its core and environment (m^2 C W^{-1}),

T_b = measured core body temperature of E-chicken (°C), and

T_e = air temperature in vicinity of the E-chicken (°C).

3.2.3 Selection of insulation covers

Simulating insulation layer of live chicken on its sensitivity to exposed temperature and air velocity is crucial. We performed tests in the laboratory with a different combination of materials under two set of wind conditions, a still air condition and an air velocity of 1.1 m s^{-1} both under an ambient temperature of 25°C and 60% relative humidity. Air velocity of 1.1 m s^{-1} was chosen since this is the average air velocity observed during preliminary commercial pre-slaughter transportation. The exposure time of E-chickens' to each wind condition was 30 min. For every combination of materials used, the E-chicken was first wrapped with a zip lock plastic bag to protect electronics from moisture during the actual field trip. An E-chicken with covers was placed at the center of a wind tunnel. A 10-inch diameter inline fan (Soler and Palau TD-250, 2400-3200 RPM, Jacksonville FL) was positioned at the inlet of the wind tunnel (fig. 3.7). The wind tunnel is 2.46 m long with a square cross section of 0.41 m wide expanding to 0.55 m. Wind speed of approximately 1.1 m s^{-1}, measured by a hot-wire anemometer (TSI 9545-A VelociCalc Meter, Shoreview, MN), was maintained at the center point of the tunnel.

Figure 3.7: Wind tunnel arrangement used in the experiment.

The power consumption of four different combinations of materials is shown in Table

3.1. The double layer of fleece fabric (fig. 3.5 B) was the most sensitive to the wind, with the heat loss increase from 7.2 W of still air to 8.5 W at wind condition of 1.1 m s^{-1}. Sensible heat loss values published in two studies at similar air velocity and temperature nearly matched the sensible heat loss values for E-chickens with double layer of fleece fabric (Gates et al., 1993; Reece and Lott, 1982).

Table 3.1: Power consumption from an electronic chicken with different insulation materials under two wind conditions (t = 25°C) averaged for 30 min.

Insulation Covers	Still air	Air velocity of 1.1 m s^{-1}
Reflective bubble wrap + carpet	6.8 W	7.4 W
Polyester fabric + carpet	7.6 W	7.8 W
Double layer of fleece fabric	7.2 W	8.5 W
Double layer of bubble wrap	6.9 W	7.3 W

3.2.4 Sensitivity of cover to wetness

Broiler transportation experiences a wet condition, not only due to precipitation throughout the year, but also intentional water treatment during extreme summer conditions. We tested the E-chickens for the response to wetness in the laboratory conditions in the wind tunnel arrangement (Table 3.2). The hypothesis was that if the E-chickens were responsive to the moisture on the surface, there would be a significant amount of water loss which was sprayed on the surface. The wind will assist the water loss; in a controlled environment, we are convinced that the only source of water loss is through evaporation from the surface.

Electronic chickens were weighed (W_{dry}) after they were wrapped with all the sensors installed to measure the power consumption at 10 s interval. All the E-chickens were individually sprayed approximately 20 g of water uniformly on the surface (W_{wet-1}) with negligible dripping and were placed at the center of a wind tunnel (fig. 3.7). The amount of water was similar to what was found to be an average amount needed to wet the average sized live chicken completely (Tao and Xin, 2002). The E-chickens were tested first at calm (no wind) and then at 1.1 m s^{-1} without re-wetting for 30 min each consecutively. The two ambient conditions in the lab were selected based on the range of vapor pressure deficit (VPD) observed during the initial Open Water trips (VPD = 1.4 and 2.8 kPa). At each ambient condition, the weight of E-chickens was recorded after each wind setting (W_{wet-2}, W_{wet-3}). The difference between W_{wet-1} and W_{wet-2} equates the water lost after the E-chickens were exposed to calm condition; whereas, the difference between W_{wet-2} and W_{wet-3} is the loss of water of 1.1 m s^{-1} wind. The average values for water loss after calm and at 1.1 m s^{-1} are 0.675 ± 0.12 g and 0.725 ± 0.09 g respectively at 1.4 kPa VPD, whereas 0.975 ± 0.83 g and 1.25 ± 0.11 g at 2.8 kPa VPD for calm and 1.1 m s^{-1} wind condition, respectively. These values of water loss after 30 min of exposure to each wind conditions were significantly less than the evaporation from live chickens calculated from equations reported by Tao and Xin (2002). The derived evaporation from Tao and Xin (2002) by assuming 2.78 kg of live weight at 1.4 kPa VPD were 0.10 mL min^{-1} $bird^{-1}$ and 0.34 mL min^{-1} $bird^{-1}$ at 0.1 m s^{-1} and 1.1 m s^{-1} respectively. And, at 2.8 kPa VPD, the derived evaporation rates were 0.18 mL min^{-1} $bird^{-1}$ and 0.42 mL min^{-1} $bird^{-1}$ at 0.1 m s^{-1} and 1.1 m s^{-1} respectively. The average power consumptions of the dry E-chickens were 5.33 W and 6.0 W and for wet E-chickens, 5.51 W and 6.37 W at calm and 1.1 m s^{-1} wind conditions at 30°C. Both low water loss and similar power consumptions of dry and wet E-chickens indicated that water loss, hence evaporative heat loss were minimal from the E-chickens. The E-chickens with existing cover materials were unable to differentiate wet vs. dry cover conditions and were not able to simulate live chickens for respiratory air exchange to lose heat. Because of this lack of sensitivity to moisture, we decided to analyze the data without differentiating dry vs. wet field conditions.

Table 3.2 Weights of dry and wet-surface electronic chickens after consecutive exposure to two wind conditions of 30 min each.

Vapor Pressure Deficit (kPa)	E-Chicken No.	W_{wet-1}[a]-W_{dry}[b] (g)	W_{wet-1}- W_{wet-2}[c] (g)	W_{wet-2}- W_{wet-3}[d] (g)
1.4 (t=25°C, RH=55%)	1	20.0	0.5	0.8
	2	19.9	0.6	0.6
	3	20.1	0.8	0.8
	4	20.0	0.5	0.7
	Average	20.0 ± 0.07	0.675 ± 0.12	0.725 ± 0.09
2.8 (t=30°C, RH=35%)	1	20.1	1.1	1.4
	2	20.0	0.9	1.2
	3	20.0	1.0	1.3
	4	20.0	0.9	1.1
	Average	20.0 ± 0.04	0.975 ± 0.83	1.25 ± 0.11

[a] W_{wet-1}: weight of initial wet E-chicken
[b] W_{dry}: weight of dry E-chicken
[c] W_{wet-2}: weight of E-chicken after calm (no wind) for 30 min
[d] W_{wet-3}: weight of E-chicken after1.1 m/s for 30 min followed by calm conditions for 30 min

3.2.5 Data collection and analysis of commercial transportation using E-chicken

All the four E-chickens were wrapped after the temperature and voltage data loggers were installed and launched. We installed the E-chickens along with other T/RH data loggers and wind loggers in empty trailers to record every 30 s. The E-chickens were located on the middle back portion of the modules (fig. 3.8), with the power switch alongside the wire mesh and accessible by a person standing on the ground. Multiple zip ties were used to hold the electronic chickens in place throughout the trip. The E-chickens were powered-on just before loading at the farm without obstructing the work flow. This allowed a maximum length of data collection during transit and holding periods since the circuit can run 2 to 3 h with a fully-charged battery during a winter trip and longer during summer. All the E-chickens were at the interior location as these were assumed to represent the environment of the majority of live chickens. Trailers had the side, tail and front boards during winter trips; the extreme winter conditions as mentioned led to the wrapping of trailers with a plastic wrap after loading. The wrap was removed once trailers reached plants. Fans with misters of various designs were used to keep the broilers cool during the loading and holding periods in extreme summer conditions.

Figure 3.8: Electronic chicken installed on the middle back of a module during commercial live-haul transportation.

The E-chickens were retrieved along with the other data loggers after live chickens were unloaded from trailers. Data were downloaded and processed by separating into transit and holding periods. The 7 min of data following the initial powering of the circuit were discarded due to pre-heating of the E-chickens to attain the target set point temperature of broilers (fig. 4.17). The wind speed data obtained from the anemometers in the near vicinity of the E-chickens were retrieved. The 5 min running average were calculated to understand the general trend of gusty wind observed (fig. 4.17). The average values for sensible heat loss for transit and holding period were obtained for all the trips with E-chickens.

4. Results and Discussions

4.1 Trips summary and the overall trailer moisture conditions

The humidity ratio values in most of the volume on the trailer for BW and BD configuration were less than 8 g/kg with a mean of 4.3 g/kg and 4.7 g/kg respectively in transit and 6.7 g/kg for the BD trips during holding (fig. 4.1 and 4.2; Table 4.1 and 4.2). 5.3% of the trailer for the BW trips during transit also recorded higher HR in the range of 8-12 g/kg with a maximum ratio of 13.5 g/kg (Table 4.1 and fig. 4.1). The maximum HR for the BD trips during holding period went as high as 19.8 g/kg (Table 4.2). These high values of humidity could have been due to the clustering of birds seen commonly during cold weather. The high HR along with low temperature (below 10°C) when relative humidity is near saturation (observed in few trips monitored, discussed later), can be detrimental for the birds during winters as the condensation of vapors can wet the broilers making them prone to hypothermia. We know that cold air can hold less amount of vapor as compared to the warmer air. Thus, one should also watch out for lower HR (6-9 g/kg) during winters which might be deceptive at conditions when the relative humidity is near saturation, and the threat of condensation of vapors persists.

For BS configuration, the mean HR during transit was lower as compared to the holding period. The temperature values also showed a high increase in the holding shed suggesting less airflow through the trailer associated with the use of single wind board on the modules. Looking at the distribution of moisture, around 24% of load volume during transit experienced HR well above the mean value (4–8 g/kg) (fig. 4.1). During holding, the condition is much worse depicting moderate moisture accumulation for 9% (12–16 g/kg) of the load, extreme rise in moisture (16–20 g/kg) in 3% of the load volume (fig. 4.2).

Table 4.1: Mean, minimum, and maximum trailer humidity ratio during transit period.

Configuration#	Ambient humidity ratio (g/kg)*	Trailer Humidity ratio (g/kg)		
		Mean*	Min	Max
Open-Water (8)	16.0 (2.6)	19.6 (4.3)	9.8	29.9
Open-No Water (4)	12.9 (5.1)	14.8 (4.6)	9.2	24.3
Boarded-Single (9)	4.8 (2.0)	6.1 (1.8)	3.0	18.3
Boarded-Double (6)	3.2 (1.3)	4.3 (1.6)	0.8	9.3
Boarded-Wrapped (5)	2.7 (1.3)	4.7 (2.0)	1.0	13.5

Number of trips monitored for each configuration mentioned in parenthesis

* Mean along with the standard deviation in parenthesis

Table 4.2: Mean, minimum, and maximum trailer humidity ratio during the holding period.

Configuration#	Ambient humidity ratio (g/kg)*	Trailer Humidity ratio (g/kg)		
		Mean*	Min	Max
Open-Water (7)	16.9 (2.9)	20.0 (3.4)	9.8	30.1
Open-No Water (3)	14.1 (4.9)	16.2 (5.0)	9.3	29.0
Boarded-Single (9)	4.9 (1.9)	7.3 (3.1)	1.2	19.6
Boarded-Double (11)	2.8 (1.1)	6.7 (2.8)	0.3	19.8

Number of trips monitored for each configuration mentioned in parenthesis

* Mean along with the standard deviation in parenthesis

For ONW configuration, the HR on trailer both during transit and holding ranged from 9 g/kg to above 24 g/kg (fig. 4.1 and 4.2). The natural ventilation seems insufficient in maintaining the uniformity during open configurations (OW and ONW) especially for OW configuration, and high moisture regions were developed both during transit and holding periods (fig. A.1 and A.6). The mean increase in humidity values during OW configuration is close to 3 g/kg during transit and 3.4 g/kg during holding (Table 4.1 and 4.2). However, there was a small change in temperature inside the trailer during OW trips. This indicates that the cooling practices used during loading and at the holding shed along with the use of fan were helpful in preventing heat accumulation for most of the locations (Liang et al., 2017). It should be noted that there are areas on the modules during OW trips with high humidity, as seen from the maximum HR of 29.9 g/kg and 30.1 g/kg during transit and holding (Table 4.1 and 4.2) respectively. And with trailer temperatures over 30°C, high humidity reduces the chicken's evaporative heat loss which is crucial for thermoregulation during hot and humid summers (Kettlewell and Moran, 1992).

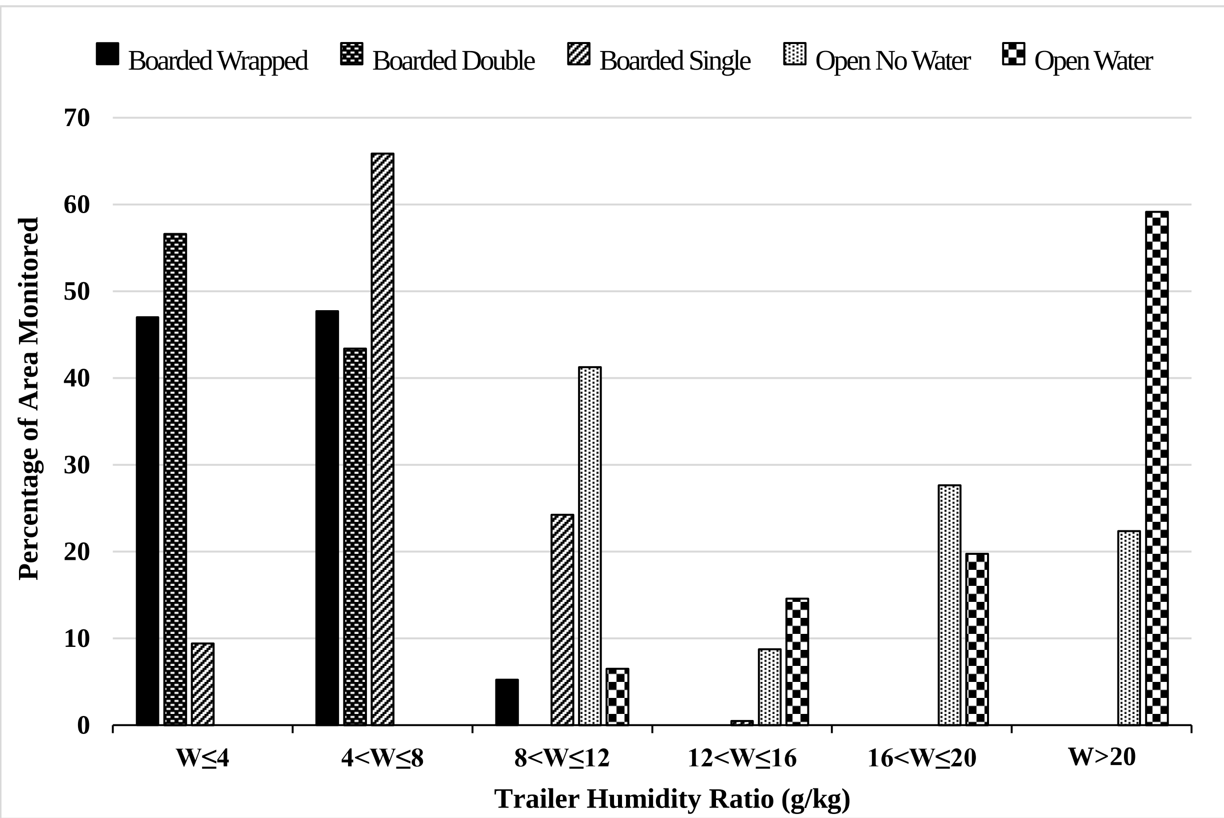


Figure 4.1: Frequency distribution for humidity ratios during transit for commercial live-haul trips with varying ventilation configurations described with legends (32 trips).

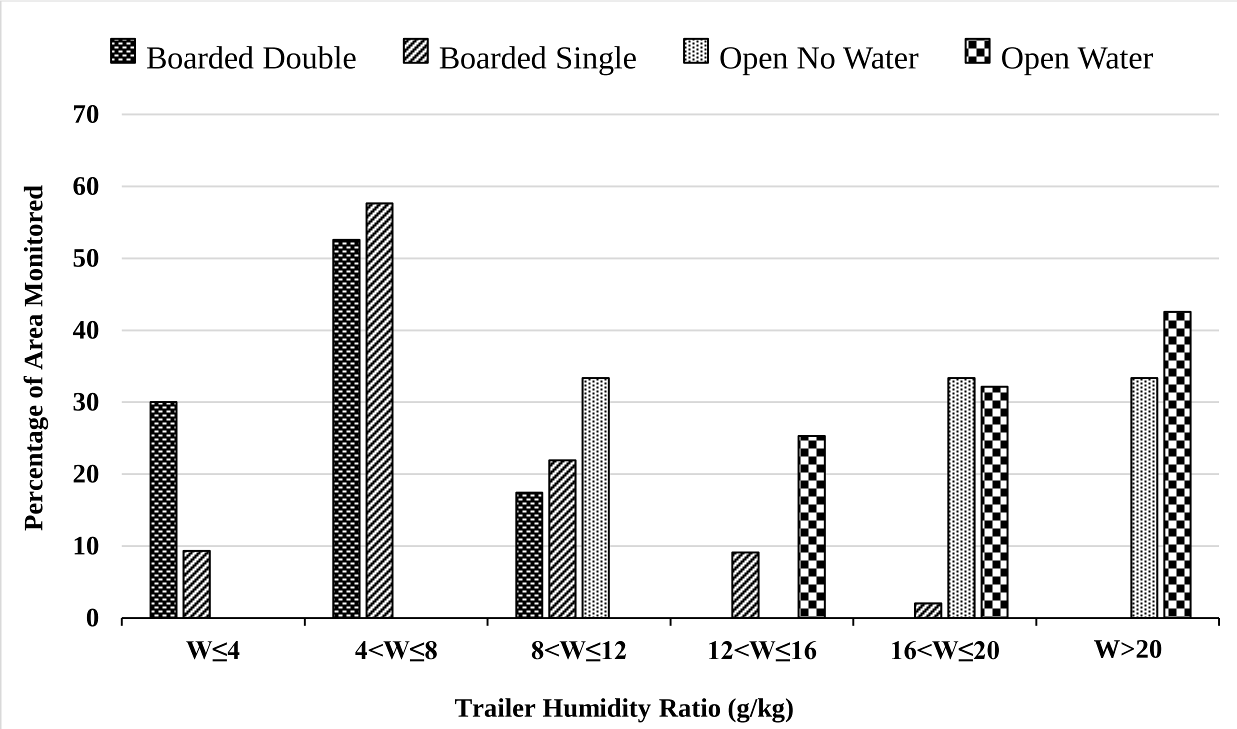


Figure 4.2: Frequency distribution for humidity ratios during holding for commercial live-haul trips with varying ventilation configurations described with legends (30 trips).

4.2 Moisture data analysis

The average increase in the HR was compared during transit and holding to understand how the use of wind boards or fan + misting practices altered the moisture condition, as well as identify any differences amongst locations along the length and width of the trailer. In the current study, the main effects: row of modules (along with the trailer length) and location of modules (interior or exterior) were statistically significant ($p < 0.05$) for transit and holding (Table 4.3 and 4.4). The ventilation configuration was moderately significant for the transit ($p = 0.06$) whereas for holding period it was not significant. All two-way interactions and three-way interactions of the main effects for the HR increase-above-ambient analysis were significant at 95 % level of significance (Table 4.3 and 4.4). Summarizing the variability in error involved in this study, trip as a random effect explained 45.7% and 48.5% of the total error, while rest 54.3% and 51.5% were experimental error during the transit and holding respectively (Table 4.3 and 4.4). Thus, a huge amount of error was removed from the analysis by taking trip to trip variability into account for the data analysis. It is important to note that all the main effects were dependent on each other and on the ambient conditions, therefore, it is crucial to look into the interactions which were highly significant (transit and holding) for any practical subject matter conclusion.

Table 4.3: Type III tests of main and interaction effects with the p-values for the transit period where HR increase-above-ambient is the response variable. Covariance parameter estimates explain the variability in error.

Covariance Estimates		**%**
Trip (vent)	0.263	45.66
Residual	0.313	54.34
Total	0.576	
Effect	**DF**	**p-value**
vent[a]	4	0.0644
row[b]	4	<.0001
location[c]	1	<.0001
row*location	4	<.0001
vent*location	4	<.0001
vent*row	16	<.0001
vent*row*location	16	<.0001

[a] vent denotes to the ventilation configuration as a factor in the analysis

[b] row denotes to the row of modules as a factor which checks variations of humidity ratio increase along the length of the trailer

[c] location denotes to the location of the modules (exterior or midline) as a factor

Table 4.4: Type III tests of main and interaction effects with the p-values for the holding period where HR increase-above-ambient is the response variable. Covariance parameter estimates explain the variability in error.

Covariance Estimates		**%**
Trip (vent)	0.302	48.48
Residual	0.321	51.52
Total	0.623	
Effect	**DF**	**p-value**
vent[a]	3	0.4269
row[b]	4	<.0001
location[c]	1	<.0001
row*location	4	<.0001
vent*location	3	<.0001
vent*row	12	<.0001
vent*row*location	12	<.0001

[a] vent denotes to the ventilation configuration as a factor in the analysis

[b] row denotes to the row of modules as a factor which checks variations of humidity ratio increase along the length of the trailer

[c] location denotes to the location of the modules (exterior or midline) as a factor

4.2.1 Mean comparisons for the HR increase-above-ambient during transit period

The comparison of main effects shows that the Open Water trips had the maximum mean HR increase-above-ambient (fig. 4.3). The mean temperature increase-above-ambient for OW ventilation was low (< 0.2°C) both during transit and holding (Liang et al., 2017). The inference for the OW configuration is that the ventilation is sufficient for heat removal both during transit and holding. However, the high moisture increase with high ambient temperature over 30°C can be a concern for the birds during transit if the relative humidity is near saturation. There were few locations for an OW trip in June, the midline of the middle and back middle rows of the module (along trailer length) only during transit that had mean relative humidity close to 80%.

Thermal cores thus pointed out are thermally uncomforting to the broilers as the capacity of the birds to lose heat through evaporation is immensely reduced at such humid conditions The importance of surface wetting to cool broilers is thus immense, and care should be taken to keep the trip duration short especially during humid conditions in summers.

For ONW trips, the mean increase in HR was lower (1.7 g/kg) as compared to the OW trips (3.2 g/kg). The ambient temperature ranged between 20-28°C for the ONW trips. Cooler ambient temperature and low temperature increase-above-ambient during transit (Liang et al., 2017), the moisture holding capacity of air decreases comparatively to OW trips. However, there were no incident of relative humidity near saturation. There were no trips in ONW configuration with water application at any stage of the trip for cooling of birds, thus reducing the amount of vapors generated due to the water application as in OW trips. Birds at these thermal conditions with no incidence of relative humidity close to saturation were most likely thermally comfortable under the present practices of the ONW trips.

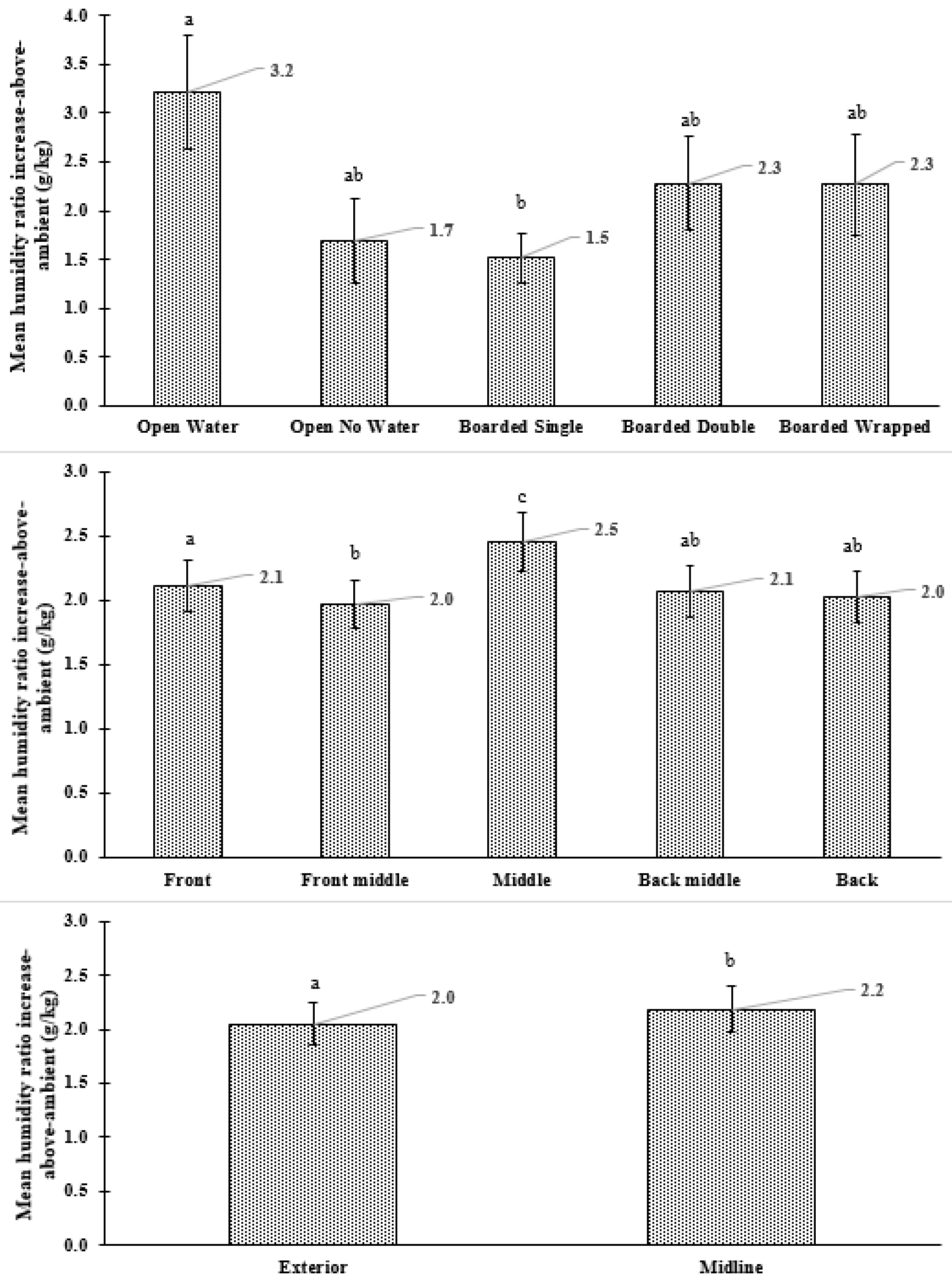


Figure 4.3: Comparison of mean HR increase-above-ambient for different levels of the main effects during transit. Means having the same letter are not significantly different.

Using wind boards did not increase the moisture tremendously during transit, as expected due to the restriction provided by wind boards to air flow. Comparing the BW and BD configuration during transit, the mean HR increase-above-ambient were almost identical, the mean temperature however increased slightly more in the BW configuration (12°C) as compared to the BD configuration (10.5°C) (Liang et al., 2017). This also points out that the industry needs to think more about the expected added advantage of the wrapping of trips, the data suggests that there is not much difference in the internal environment of the trailer suggested by heat and moisture during the transit.

The variations along the row of modules on the trailers were statistically significant (Table 4.3). The middle row of the module had the highest mean HR increase-above-ambient i.e. 2.5 g/kg (fig. 4.3); suggesting the moisture accumulation in the middle portion of the trailer during transit. Exterior and midline for each module were statistically different from each other, the midline of the modules yielding higher HR increase-above-ambient (fig. 4.3). This suggests a thermal core right at the center of the trailer during transit. It was found that the air flow was higher towards the exterior of any modules as compared to the midline. The wind data were gathered for a trip in June, during transit the mean wind speed at the exterior and midline were 2.65 m/s and 0.72 m/s respectively. The reduced air flow in the midline was due to the restriction by the birds resulting in less penetration of air towards the midline of the modules. Hoxey et al. (1996) suggested that the air inlet is at the back while the outlet is towards the front of the trailer. The results of our study suggested no clear inlet and outlet. The use of headboards in few trips might have restricted the air flow and contributed to comparatively high values for the front modules during transit.

All the two-way and three-way interactions amongst the main effects were statistically significant (Table 4.3). Table A.1 represents the mean comparisons at all points on the modules for all configurations. Some of the details regarding the variations in all the trailer locations can be understood in a better way if we look into each configuration.

4.2.1.1 Open-Water configuration

Open-Water configuration although had no wind boards, non-uniformity in air distribution was observed, the front middle row of modules had the highest increase in moisture and the locations on an average showed more moisture as compared to midline (fig. 4.4). It is suspected that the sun rays falling on the exterior might have increased the evaporation of water that was sprayed at the farm. Also, there might be some carry-over effect of wetting the modules at the farm which may not have penetrated into the center of the module. The air flow achieved may not be enough to remove moisture at an ambient temperature above 30°C (Liang et al., 2017). Also, the high HR increase might be due to the enhanced moisture carrying capacity of the warm air during OW trips. For an OW trip in June, the midline of the middle and back middle rows had mean relative humidity close to 80%. Relative humidity near saturation during warmer ambient conditions can lead to hyperthermia as both convective and evaporative heat loss can be restricted in these conditions. Fig. A.1 can be referred for the 3-D visual comparisons of the moisture development at various locations.

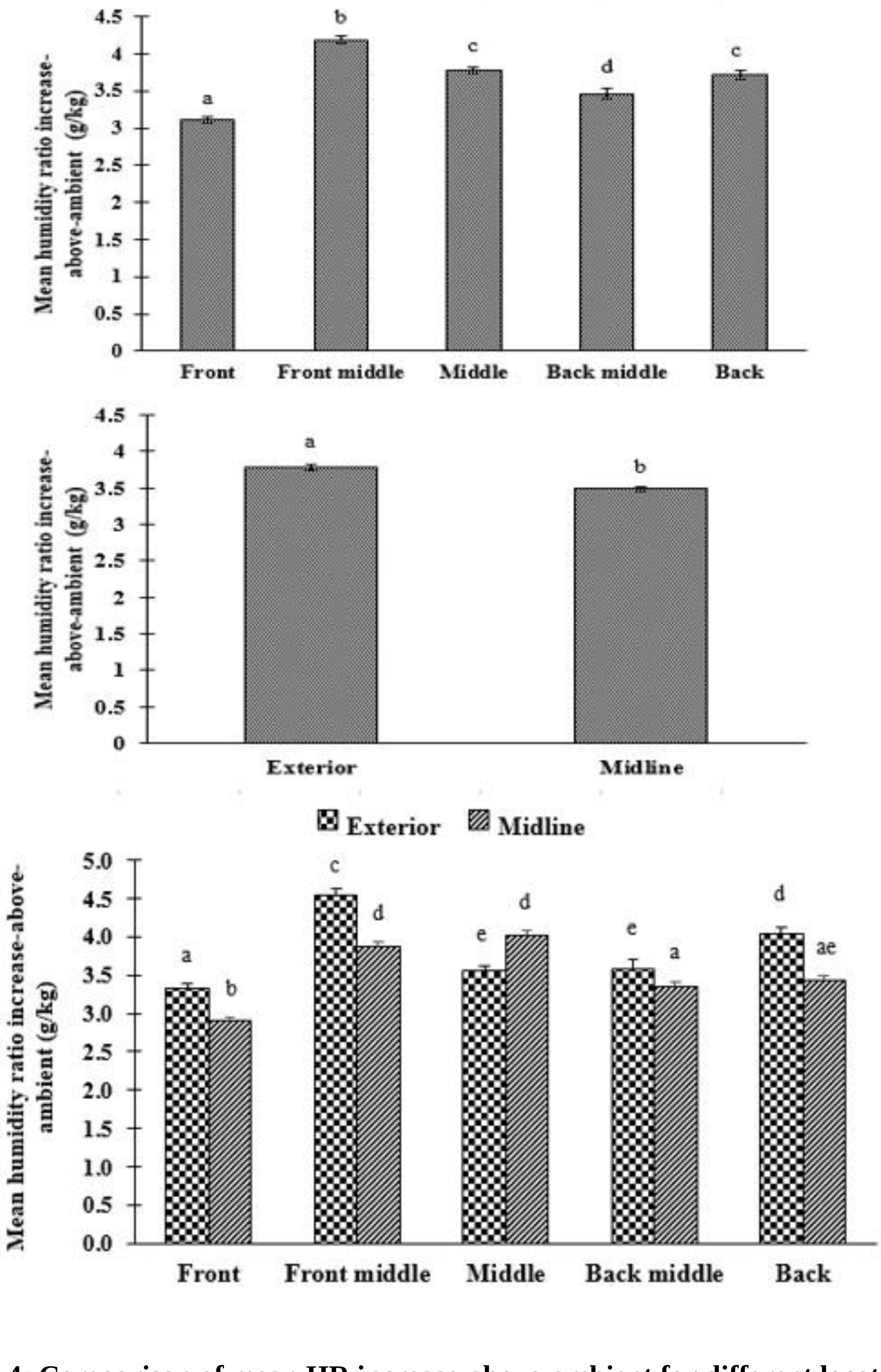


Figure 4.4: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Open-Water ventilation configuration during transit. Means having the same letter are not significantly different.

4.2.1.2 Open-No Water configuration

The HR increase-above-ambient on the modules for ONW trips had the uniform increase along the trailer rows and the locations on the modules (fig. 4.5). However, the front row showed slightly higher HR increase, which can be attributed to the air flow restriction provided by the truck. No location showed relative humidity near saturation, and thus the HR increase values suggest thermally suited conditions to broiler chickens which can also be related to the milder ambient conditions for ONW trips as compared to the OW trips. Fig. A.2 can be referred for the 3-D visual comparisons of the moisture development at various locations during ONW transit.

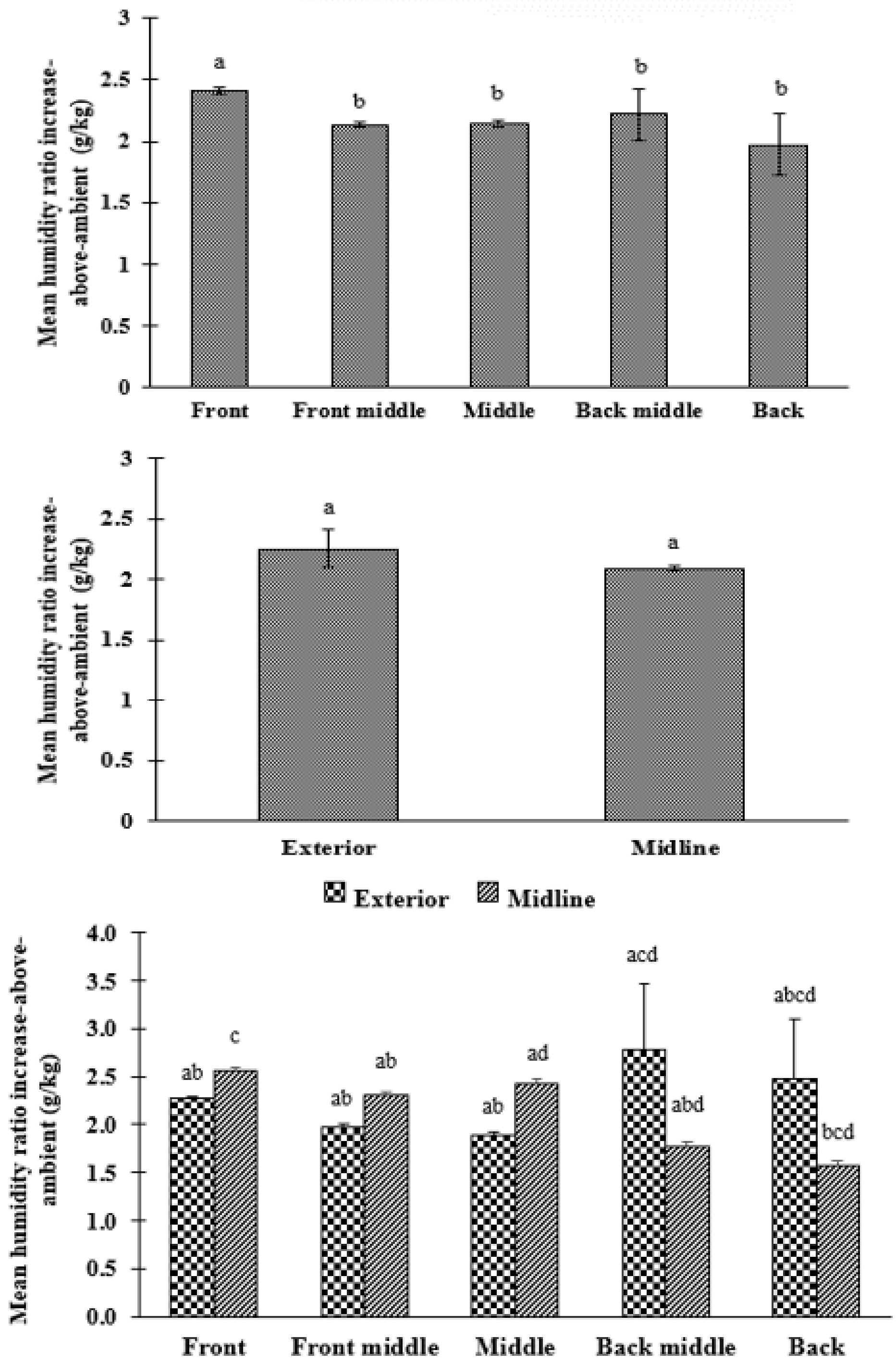


Figure 4.5: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Open-No Water ventilation configuration during transit. Means having the same letter are not significantly different.

4.2.1.3 Boarded-Single configuration

Boarded-Single trips during transit overall had the most HR increase-above-ambient in the front and middle rows. Midline locations on average had higher HR increase, middle midline location had a thermal load suggested by the highest increase in HR (fig. 4.6). High moisture without saturation might help the broilers to lose less vapor through respiration and thus restrict the evaporative heat loss during cooler ambient conditions. Fig. A.3 depicts the 3-D distribution of HR increase-above-ambient for the Overall, the moisture distribution for BS trips did not suggest any serious discrepancy in the management practices.

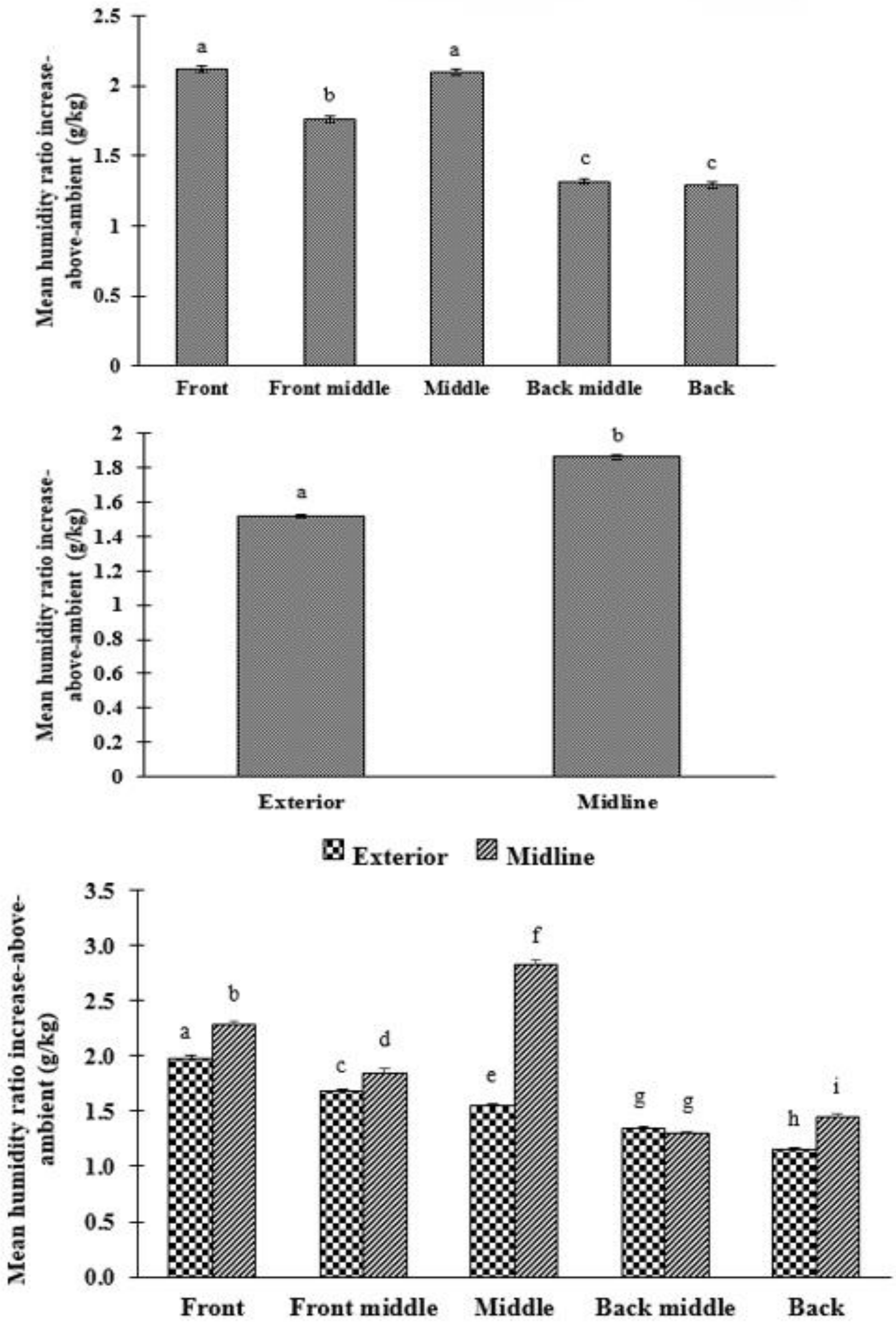


Figure 4.6: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Boarded-Single ventilation configuration during transit. Means having the same letter are not significantly different.

4.2.1.4 Boarded-Double configuration

The high variability in HR increase-above-ambient amongst the BD trips along different rows of the modules and locations on each module (fig. 4.7). The wind board application, in general, is applied to achieve uniform environment by restricting the air flow. The higher values in midline suggest that the chickens might have crowded in the midline of the modules and tried to stay away from the exterior. No near saturation conditions were located and thus there were no chances of condensation of water which otherwise might have led to the wetting of broilers and thus making chickens prone to hypothermia. Fig A.4 describes the 3-D distribution of the HR increase-above-ambient on BD trips during transit.

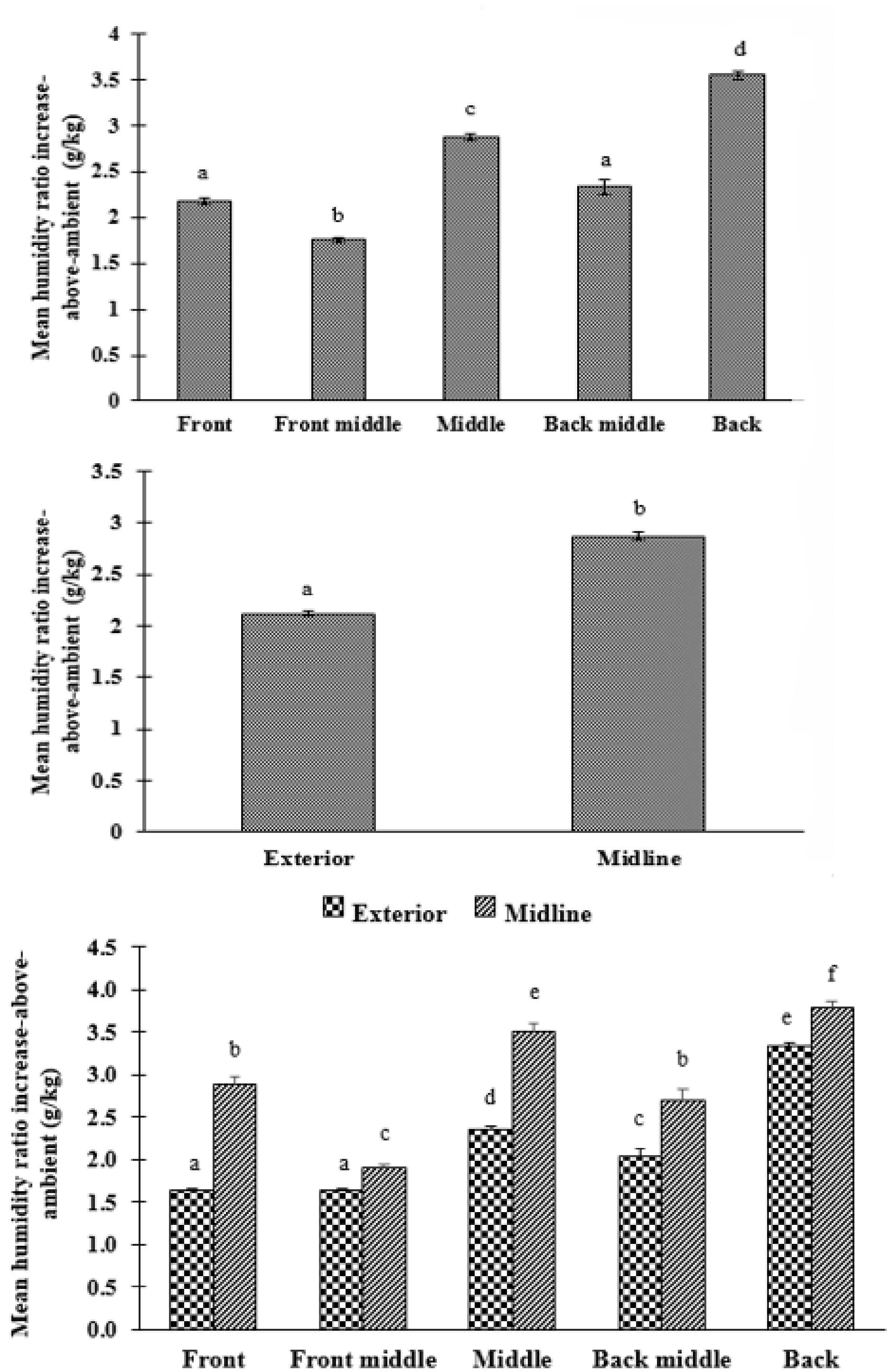


Figure 4.7: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Boarded-Double ventilation configuration during transit. Means having the same letter are not significantly different.

4.2.1.5 Boarded-Wrapped configuration

The middle rows and the exterior locations overall had the most HR increase-above-ambient during transit of BW trips (fig. 4.8). The BW configuration must have trapped the moisture at the exterior locations due to the presence of plastic wraps. The non-uniform distribution suggests that the wrapping used were not very effective and in no sense improved the uniformity as compared to the BD trips. This might be due to the non-uniform wrapping, unknown distribution of the chickens during loading or their shift of locations within each compartment during transit. However, no serious concerns can be raised as the moisture increase might help the broilers to restrict their evaporative heat loss through respiration. And, no location had the moisture level near saturation which reduces the risk of chickens getting wet due to vapor condensation and thus suffering from hypothermia. Care must be taken by the companies to apply the wind boards along with the wrap in a uniform manner. Fig. A.5 can be referred for a 3-D visual description of the moisture distribution during transit of BW trips.

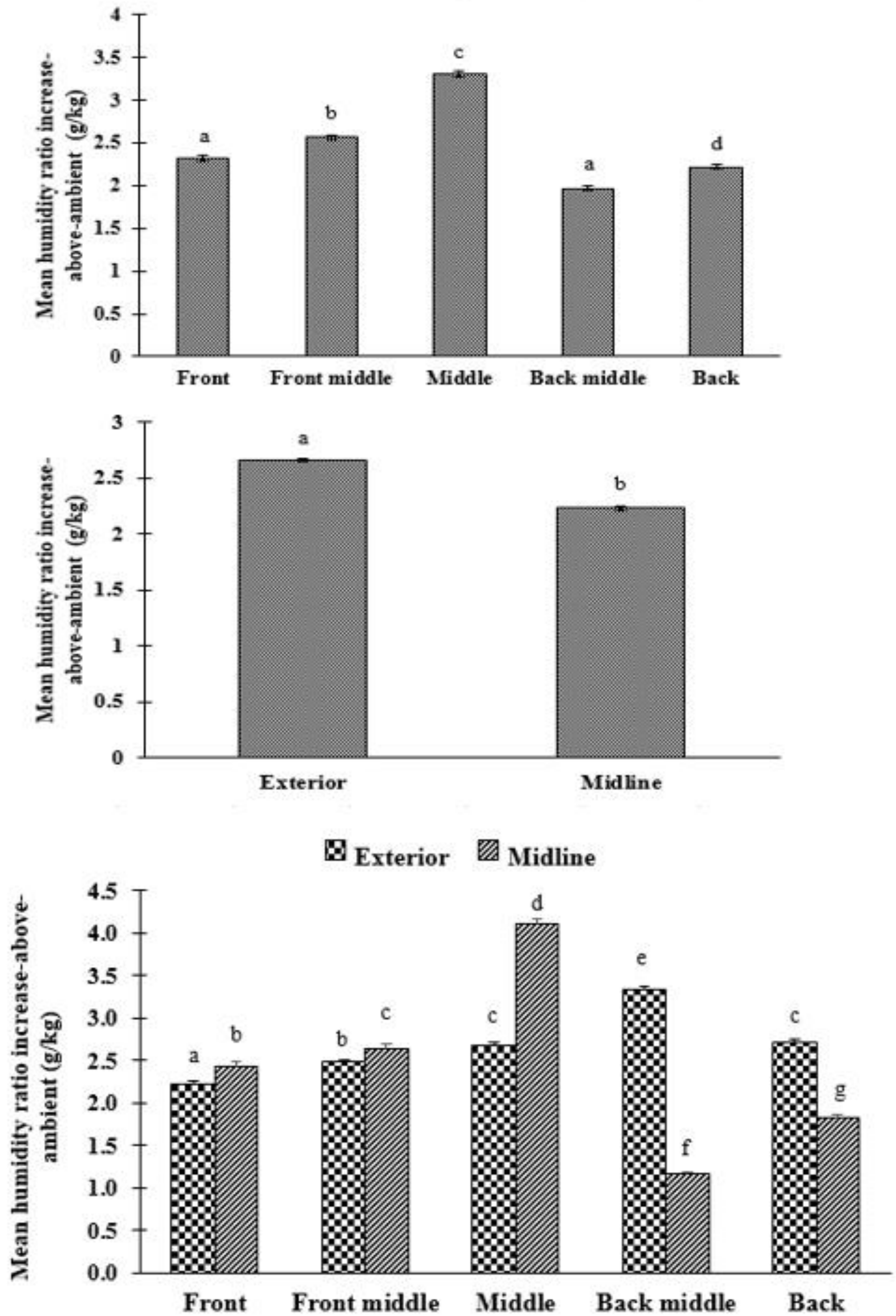


Figure 4.8: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Boarded-Wrapped ventilation configuration during transit. Means having the same letter are not significantly different.

4.2.2 Mean comparisons for the HR increase-above-ambient during holding period

The mean humidity increase for the OW configuration was decreased considerably during holding (2.3 g/kg) as compared to transit (3.2 g/kg). This can be attributed to the more uniform air distribution and better moisture removal in the holding shed by using fans. For holding, the mean HR increase was very similar for each configuration as also suggested by the non-significance of the ventilation configuration during holding (Table 4.4, fig 4.9).

The ambient temperature ranged between 20-28°C for the ONW trips. Cooler ambient temperature and low increase in temperature during transit and holding (Liang et al., 2017), the moisture holding capacity of air decreases comparatively to OW trips. However, there were no locations with relative humidity near saturation. Birds at these thermal conditions with no incidence of relative humidity close to saturation were most likely thermally comfortable under the present practices of the ONW trips both during holding.

However, during holding, especially for the BD configuration there was a high rise in moisture (3.4 g/kg). The temperature rise experienced was nearly 10°C (Liang et al., 2017) in the BD configuration during holding. Wetting of broilers at cold temperature might take place at humidity near saturation (not observed in this study) which can lead to hypothermia. To be on a safer side, companies might need to think about increasing air flow needs by blowing some warm wind with the help of heating elements and fans.

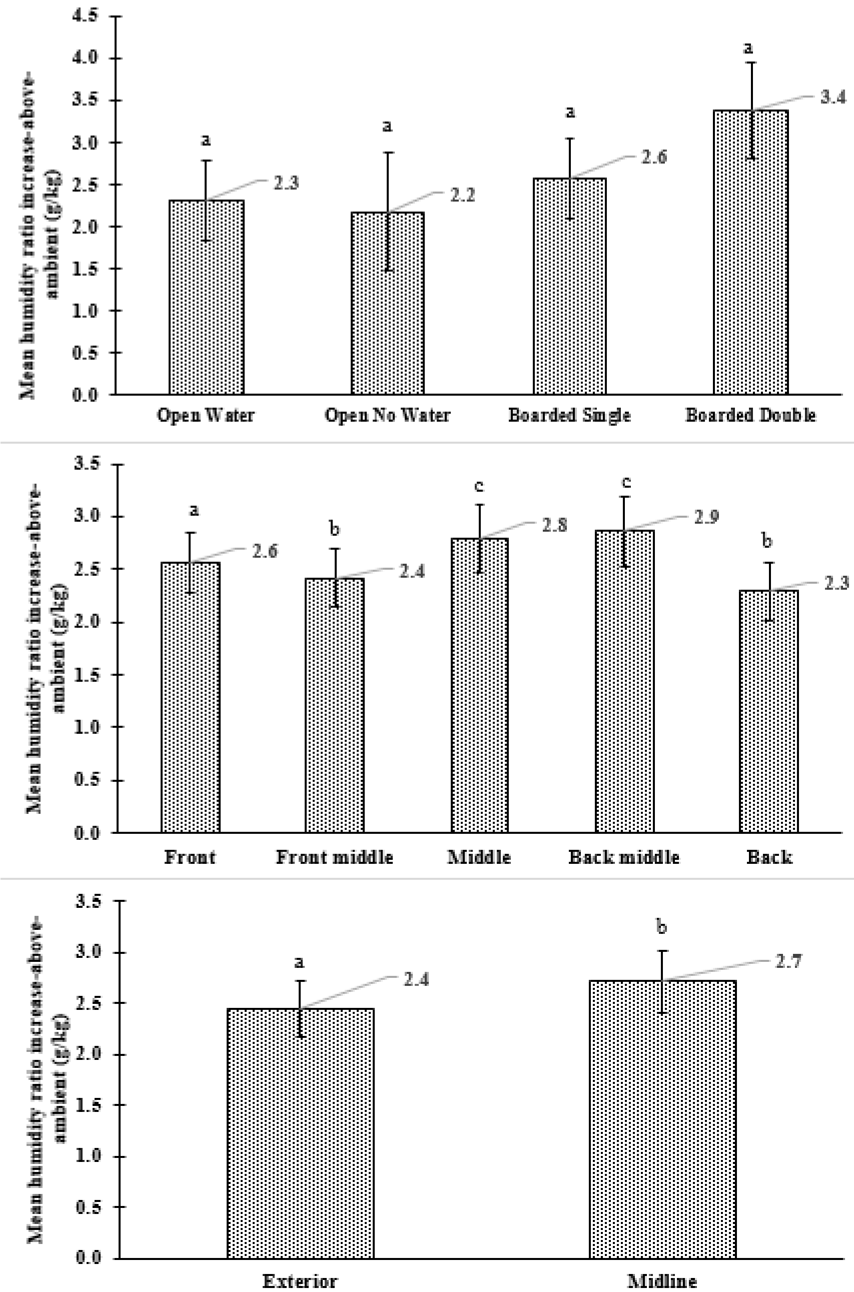


Figure 4.9: Comparison of mean HR increase-above-ambient for different levels of the main effects during holding. Means having the same letter are not significantly different.

The variations along the row of modules on the trailers were statistically significant (Table 4.4). The middle and back middle modules had the higher values as compared to the other three row locations. Exterior and midline for each module were statistically different from each other, the midline of the modules yielding higher HR values (fig. 4.9). This suggests a thermal core right at the center of the trailer both during holding. It is speculated that the air flow is better towards the exterior of any modules as compared to the midline. For holding, the mean wind speed observed during an OW trip was 1.38 m/s at the exterior and 0.49 m/s at the midline. The variations (fig. 4.9) inside the holding shed along the rows indicate the need for uniform air flow that can be achieved by the fans in the holding shed.

All the two-way and three-way interactions amongst the main effects during holding period were statistically significant (Table 4.4). Table A.2 represent the mean comparisons at all points on the modules for all configurations. All the ventilation configurations were looked into detail for the trends in HR increase within the trailers during holding.

4.2.2.1 Open-Water configuration

For holding period, the HR increase-above-ambient tends to be highly variable for OW configuration along the row of modules exterior or midline (fig. 4.10). The midline locations had higher HR increase-above-ambient from the exterior locations. The OW configuration, especially in the back middle location, needs a high increment in air flow for better moisture removal (fig. A.6). The high increase in moisture might be due to warmer air in the environment which can hold more moisture as compared to the cooler air. High moisture conditions during warmer ambient conditions can lead to hyperthermia as both convective and evaporative heat loss can be restricted in these conditions.

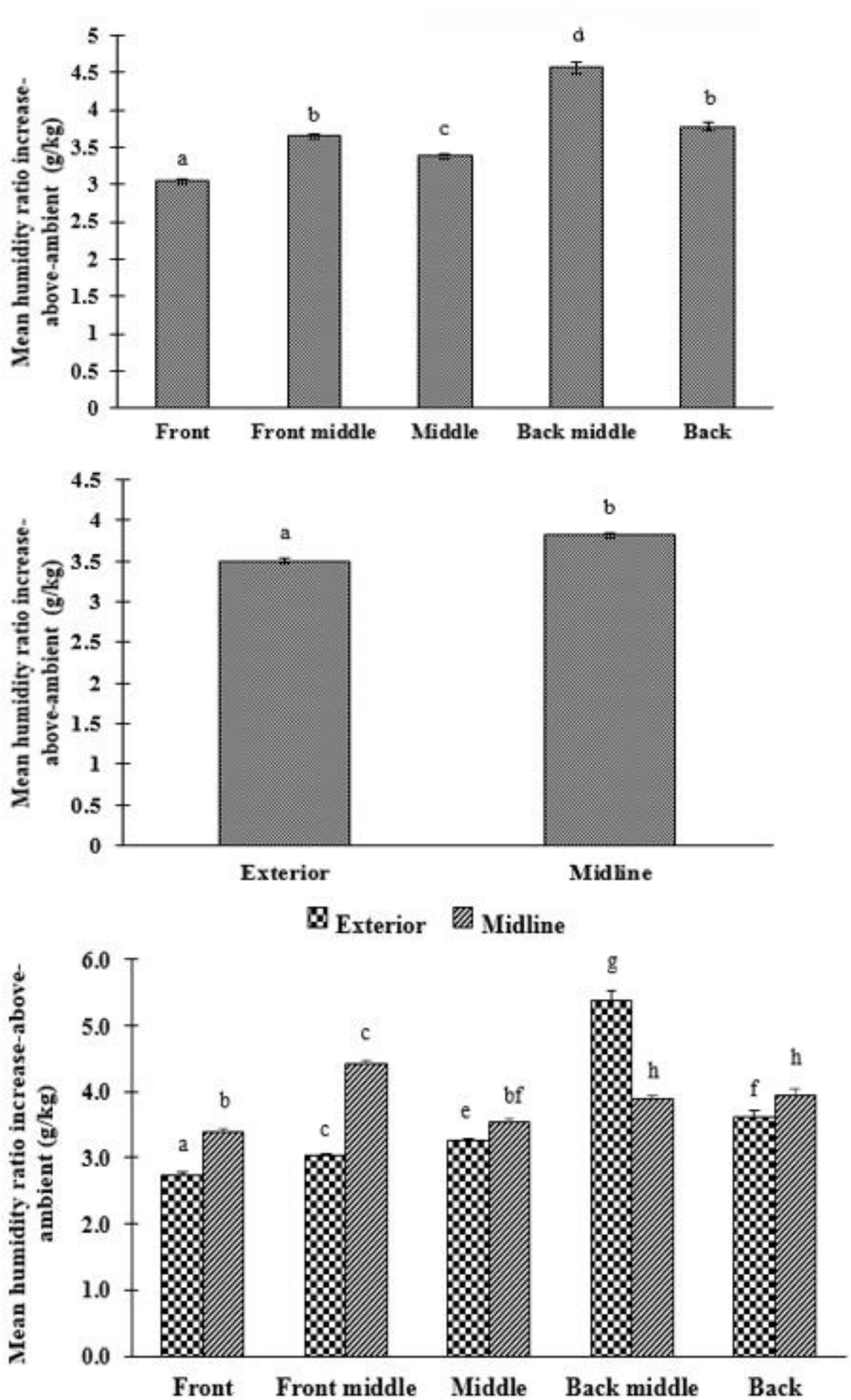
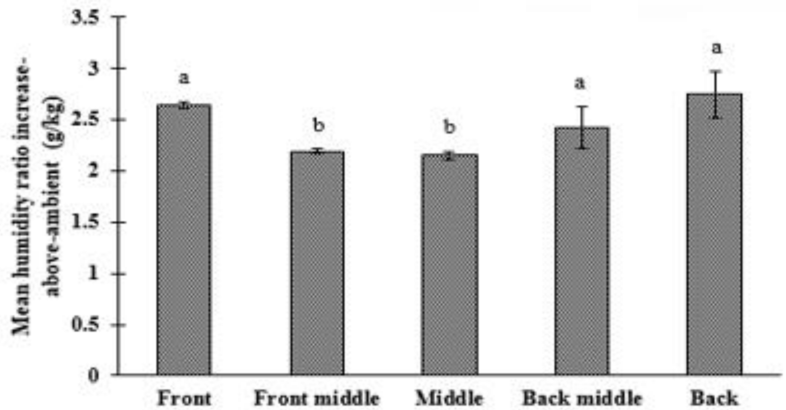
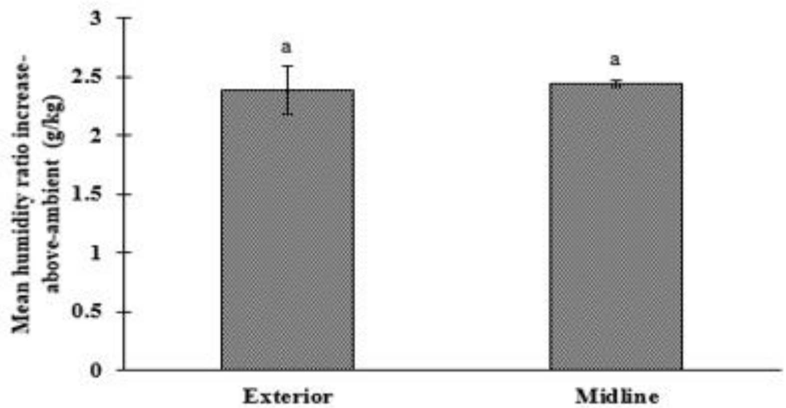


Figure 4.10: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Open-Water ventilation configuration during holding. Means having the same letter are not significantly different.

4.2.2.2 Open-No Water configuration

For ONW trips the distribution of HR increase-above-ambient is almost uniform along the rows and the exterior or midline locations on the modules (fig. 4.11). The front middle and middle rows had lower HR increase, depicting better air flow in these rows at the holding shed. The management practices used were good enough to keep the moisture level under control. This can also be due to the milder ambient conditions during ONW trips. Fig. A.7 can be referred for the 3-D distribution of the HR increase-above-ambient during ONW trips in holding.





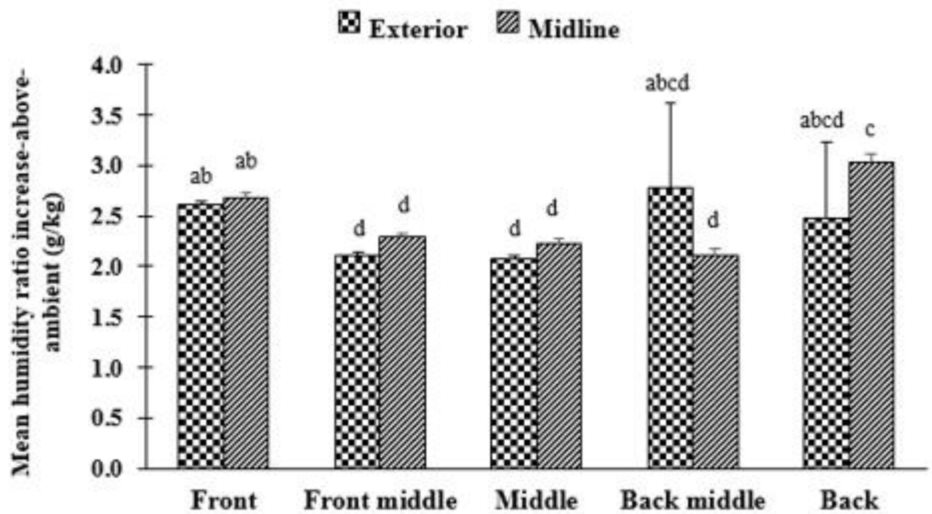


Figure 4.11: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Open-No Water ventilation configuration during holding. Means having the same letter are not significantly different.

4.2.2.3 Boarded-Single configuration

For BS trips, the moisture accumulation was variable along different locations on the trailer as seen in fig. 4.12 and A.8. Back middle row had the most moisture accumulation, with the midline of back middle suggesting a thermal load (fig. 4.12). However, no location had the relative humidity near saturation, which might be helpful for the chickens to lose less evaporative heat through respiration. The temperature increase-above-ambient were not analyzed in this literature (temperature results only for main effects used to explain some the results). However, the current project aims to get the extensive analysis of temperature during the transit and holding shed. Based on the humidity ratio increase, no serious concerns can be raised to improve the management practices.

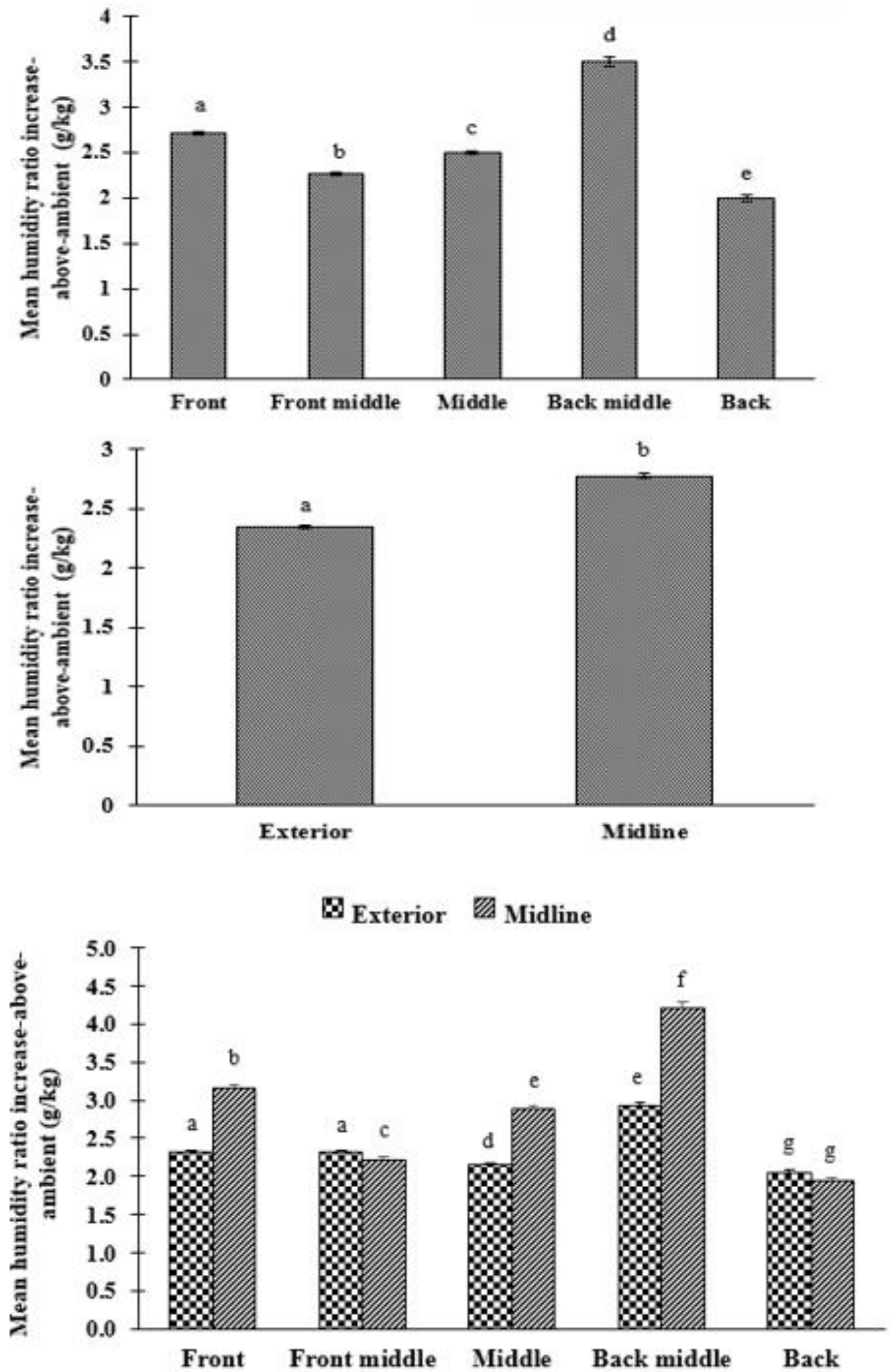


Figure 4.12: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Boarded-Single ventilation configuration during holding. Means having the same letter are not significantly different.

4.2.2.4 Boarded-Double configuration

High variability on the BD trips was found along the rows of modules and also along the exterior or midline locations (fig. 4.13). The middle row had the most accumulation of moisture, and the exterior of the modules on average had higher HR increase-above-ambient. The non-uniform distribution of wind boards might be the reasons for the variability in moisture accumulation. This also indicates that the wind boards during holding create a restriction for air flow which leads to the moisture accumulation and thus, higher air flow is required during holding when the wind boards are on. However, all the decisions should be taken considering both temperature and humidity variations.

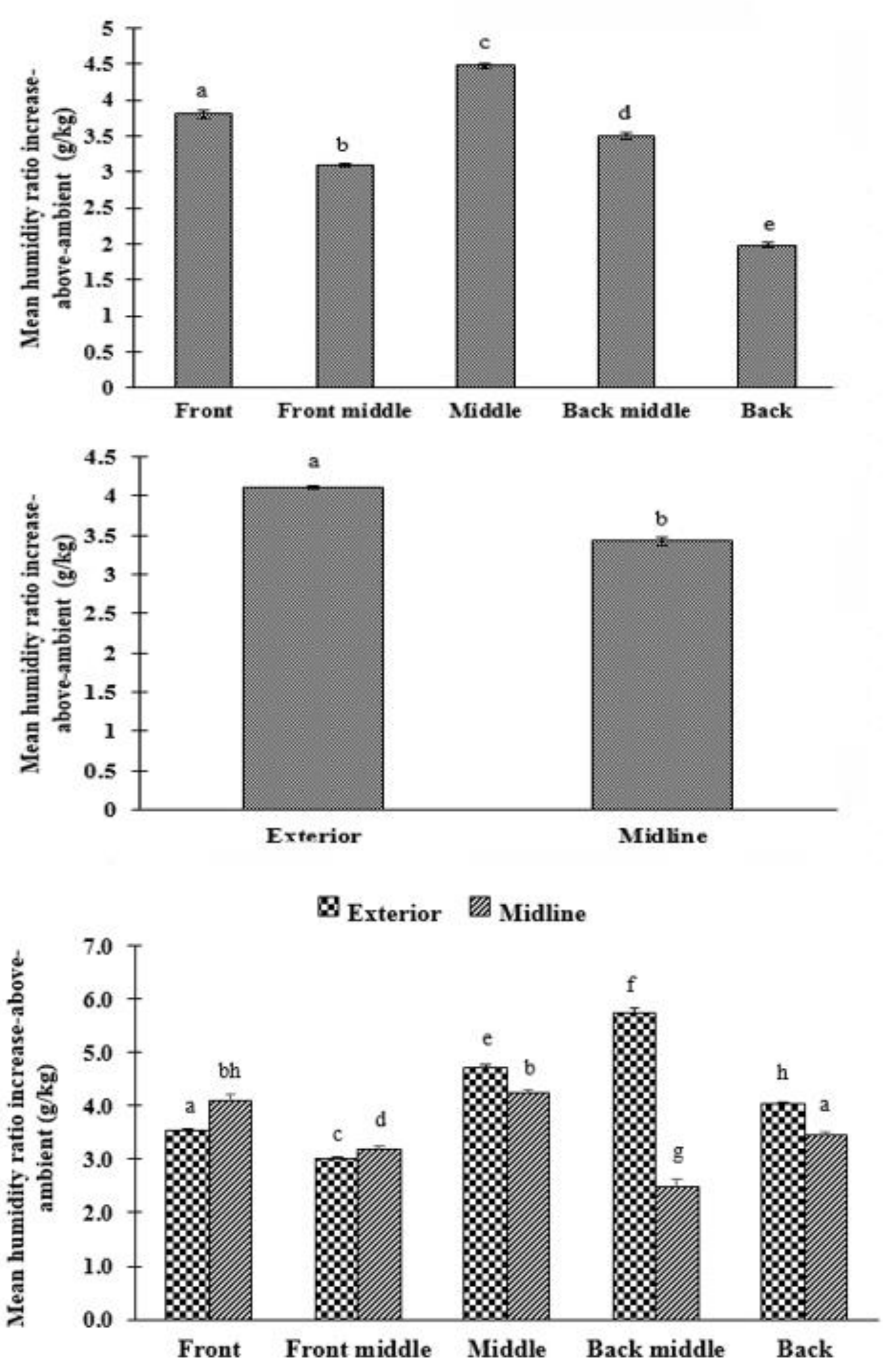


Figure 4.13: Comparison of mean HR increase-above-ambient for different locations on the chicken trailer under Boarded-Double ventilation configuration during holding. Means having the same letter are not significantly different.

4.3 Analysis of exterior and middle location on modules during hot weather trips

In the current study, the AET and THVI values were calculated for one of the Open-Water trips in June as described in section 3.1.2. As per Mitchell and Kettlewell (1998), AET values above 65°C is dangerous for the birds. The AET values in the current study for all the locations along the trailer suggest extremely hyperthermic conditions (fig. 4.14). The exterior locations' AET were overall slightly less as compared to the middle of the modules attributing to the reduced air flow in the middle of the module. The average wind speed recorded for the exterior and midline were 2.65 and 0.72 m/s respectively during transit. For holding, the mean wind speed observed was 1.38 m/s at the exterior and 0.49 m/s at the midline. This also suggests that broilers at the midline of modules were exposed to slightly more extreme temperature and humidity as compared to the exterior locations (fig. 4.14).

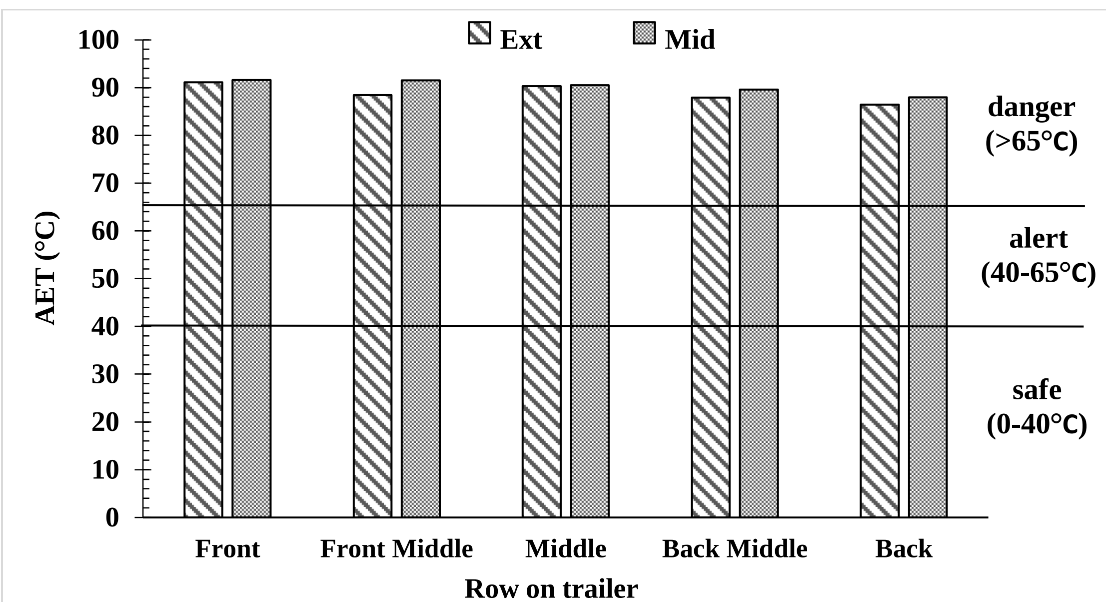


Figure 4.14: AET comparison of exterior and midline location on modules along the length of live haul trailer for a hot trip in June (zone of homeostasis drawn for reference).

The exterior of the modules had less THVI values as compared to the midline (fig. 4.15), also indicated by the AET values. However, the THVI values which also considered the exposure time of broilers to certain thermal conditions do not indicate dangerous thermal conditions for the broilers. The average THVI value (32.1°C) in the middle of the modules and the average exterior value (29.6°C) lied within the region of normal homeostasis (fig. 1.6) for 198 min (46 min in transit and 152 min in holding) of thermal exposure.

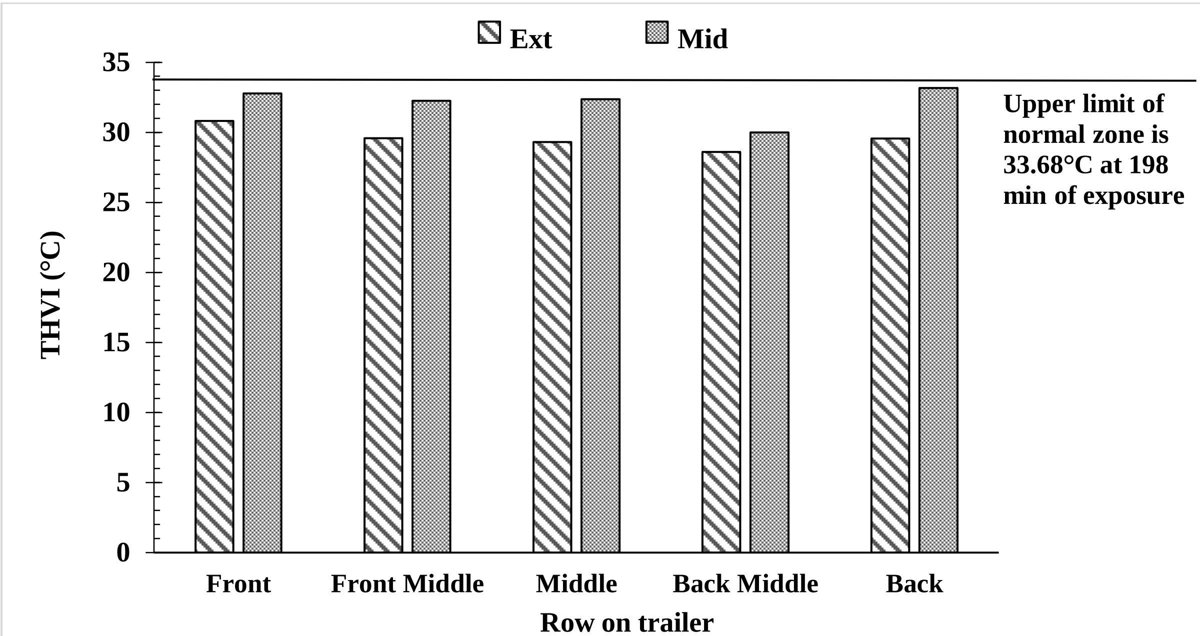


Figure 4.15: THVI comparison of exterior and midline location on modules along the length of live haul trailer for a summer trip.

In a separate Open-Water trip in July with average ambient conditions of 31°C dry-bulb temperature and 65% relative humidity (50 min transit and 82 min holding), we measured the core-body temperature of eight live chickens (data not shown). The objective was to understand the increase in body temperature of live birds with the varying wind in hot ambient conditions. All anemometers were located in the middle row which had all eight live birds along with the temperature-humidity data loggers. The mean AET for midline and exterior were 85.6°C and 83.3°C respectively; both values suggest dangerous conditions. The THVI for midline and exterior were 34.1°C and 31.2°C respectively, suggesting normal conditions for a trip of 132 min duration. The midline values for both AET and THVI were comparatively higher from an exterior location. The average wind speed recorded for the exterior and midline were 1.92 and 0.59 m/s respectively during transit. For holding, the mean wind speed observed was 0.72 m/s at the exterior and 0.24 m/s at the midline. The midline and the exterior comparison are similar to the discussion for the June trip.

AET and THVI results contradicted each other in both trips discussed above, with AET suggesting dangerous thermal conditions and THVI suggesting normal conditions. The contradiction may be due to the different methodologies used to derive these indexes. THVI used wind velocity and exposure time of broilers to trailer thermal conditions in addition to dry-bulb temperature and relative humidity that was used by AET. The comfort zones derived from AET values used not only the core-body temperature of birds (as used in THVI) but also the blood pH and blood gas disturbances as physiological responses. This allows AET to incorporate the conditions when the core-body temperature did not rise much, but still, the birds are uncomfortable and striving hard through other physiological mechanisms like panting to prevent core-body temperature increase. Secondly, the observed wind at many locations was outside the range of the THVI reported. Thus we adjusted the wind for calculating THVI. The small range of the wind that can be applied for THVI calculation reduces any extreme wind effects on the analysis. Therefore, uncertainty exists in applying THVI for higher winds. Thirdly, the birds that were used to derive the comfort zones using AET were kept in transport crates inside a chamber for 180 min at calm wind condition for various combination of temperature and relative humidity (Mitchell and Kettlewell, 1998). AET values should, therefore, be calculated for trips of 180 min or longer. Use of no wind, blood pH and gas disturbance in addition to core-body temperature as physiological responses, somewhat explains the development of dangerous conditions when

THVI suggests normal conditions. More research is needed to reconsile these heat indexes to allow accurate determination of broiler comfort level on the basis of measured thermal parameters. Future improvements should be made to incorporate the higher range of experienced wind parameter.

4.4 Electronic chickens performance in lab conditions

All four chickens were tested in the laboratory to analyze their behavior in different ambient conditions (fig. 4.16). The environmental parameters are chosen as to cover the range of ambient conditions experienced during summer transportation in the Southern U.S. Four temperatures 16, 21, 25 and 30°C are chosen. Four different wind conditions i.e. 0, 0.60, 1.10 and 1.60 m s^{-1} were established in the wind tunnel (fig. 3.6) fitted with a fan (Soler and Palau TD-250, 2400-3200 RPM, Jacksonville FL) for each of the four temperatures. Target temperatures are established by changing thermostat settings in the lab. Temperature and air velocity are measured using a hot-wire anemometer (TSI 9565-A, ±0.015 m s^{-1} and ±0.3°C).

Figure 4.16 gives the power consumption of all four chickens along with the average values at various ambient conditions. Data indicated that the chickens are sensitive to the wind and temperature. The variations in power consumption/heat loss values are as hypothesized; increasing wind increases heat loss whereas increasing temperature decreases heat loss (Genc and Portier, 2005). The increase in ambient temperature decreases the difference between the fixed body temperature and the ambient temperature. Therefore as the temperature gradient decreases, power consumption (heat loss) decreases; expected from the sensible heat loss formula discussed above. Increasing wind assists sensible heat loss by replacing hot air close to the chicken surface with cold air, and thus there is an increase in power consumption/heat loss in chickens. We can observe in figure 4.15 that the decrease is more in 16°C going to 21°C as compared to other drops from 21°C to 25°C and 25°C to 30°C. Wind tunnel helped reduce wind turbulence and keeping the constant environment at each temperature and wind values. All chickens behaved similarly in all ambient conditions and the slight variation in power consumption/heat loss is likely due to slight variation in the wrapping of E-chickens. Therefore, E-chickens are treated equally in the field data without differentiating individual chicken.

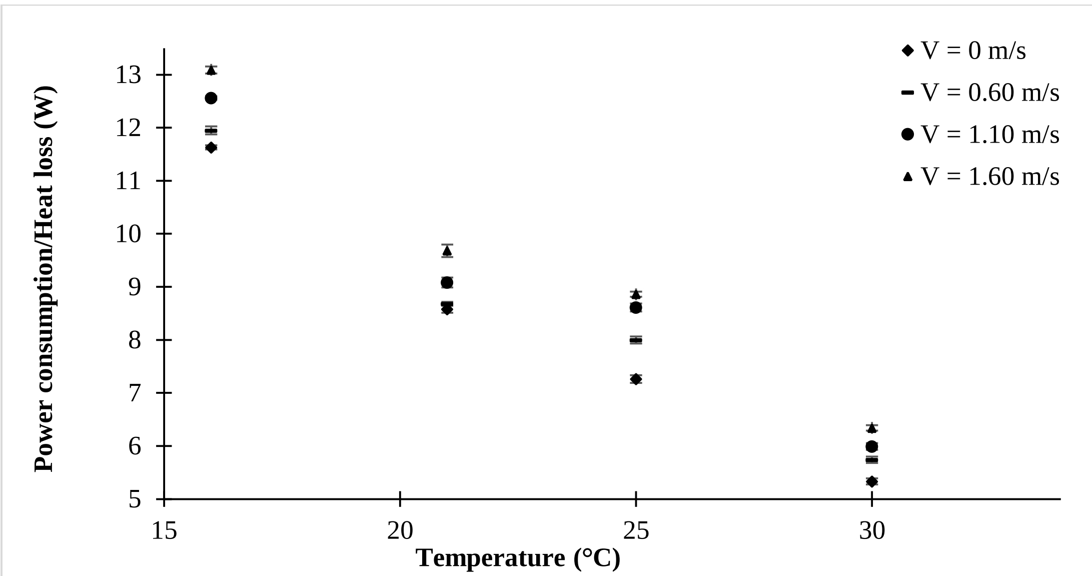


Figure 4.16: Power consumption (mean and standard deviation) of four E-chickens at different wind and temperature under wind tunnel conditions.

From table 4.5 we can see that wind and power consumption has a strong positive correlation whereas temperature and power consumption has a strong negative correlation which is significant at 99% confidence level.

Table 4.5: Pearson Correlation coefficient for wind and temperature with average power consumption at each temperature and wind values used in laboratory tests.

Temperature (°C)	Correlation Coefficient	Wind (m/s)	Correlation Coefficient
16	0.99*	0	-0.99*
21	0.94*	0.60	-0.98*
25	0.99*	1.10	-0.97*
30	0.99*	1.60	-0.98*

* Signifies significant value at 99 % confidence level.

4.5 Sensible heat loss from E-chicken in transit and holding

Before the commercial live haul trips, data loggers along with E-chickens were installed at selected central location on the trailer. Data from all four chickens were analyzed and treated in similar fashion as they were found to behave similarly under laboratory conditions. Data were analyzed to investigate the effect of changing the ambient temperature on the power consumption of E-chickens and thus to the changing management practices. Eight commercial trips including transit as well as holding period were covered with E-chickens. These trips were divided based on the number of pull-on plastic wind-boards that were installed on the sides of the modules to protect broilers from extreme winter. Fully boarded trips had almost complete coverage of wind-boards on the sides, partially boarded trips had nearly half coverage on the sides, and open trips had no board. This division of the trips is different from the division based on the ventilation configuration used for the earlier moisture load analysis (Open-Water, Open-No Water, Boarded-Single, Boarded-Double, and Boarded-Wrapped). We have reduced the division to open, partially boarded and fully boarded trips due to the fewer number of trips that were covered with E-chickens for each ventilation configuration. The number of wind-boards used was depended on the severity of winter. The ambient temperature in the eight trips ranged from -17.0°C to 33.5°C and wind ranged from 0 to 1.2 m s^{-1}. Table 4.6 illustrates the data of E-chickens on commercial trips with extreme conditions. In winter, the maximum heat loss value recorded was 20.3 W and the minimum in summer was 4.5 W. Both these values suggest that the birds were thermally uncomforted. The wind was negligible during winter as the trailers had double boards on the sides, front and the tail board at the ends of the trailers. The trips with the plastic wrap during the transit also restricted the wind.

Table 4.6: Environmental conditions and sensible heat loss observed during eight commercial live haul trips.

	Fully Boarded	Partially Boarded	Open
Ambient temperature T_a Range (°C)	-17.0 – 3.0	20.2 – 20.3	28.3 – 33.5
Air temperature in trailer, T_e Range (°C)	-3.9 – 22.2	21.5 – 21.6	25.3 – 33.2
ΔT (T_e-T_a) in transit Mean ± SD (°C)	11.3 ± 5.5	1.3 ± 0.01	0.9 ± 1.6
ΔT (T_e-T_a) in holding Mean ± SD (°C)	10.9 ± 5.2	1.3 ± 0.05	-3.2 ± 1.5
Estimated V in transit (m s^{-1})			
Range	0 – 0	No data	0.1 – 1.2
Mean ± SD	0 ± 0	No data	0.7 ± 0.3
Sensible heat loss in transit, P Range (W)	8.2 – 20.3	8 – 8.1	4.5 – 6.7
Sensible heat loss in holding, P Range (W)	6.4 – 16.7	6.3 – 7.7	4.9 – 7.3

Figure 4.17 shows the heat loss in one of the E-chickens during a summer trip and its variation along with the wind and ambient temperature. After initial high peak for heat loss which increased the internal temperature approximately near 41°C, it can be noticed that the heat loss decreased during the transit when the wind increased, an apparent drop in external temperature.

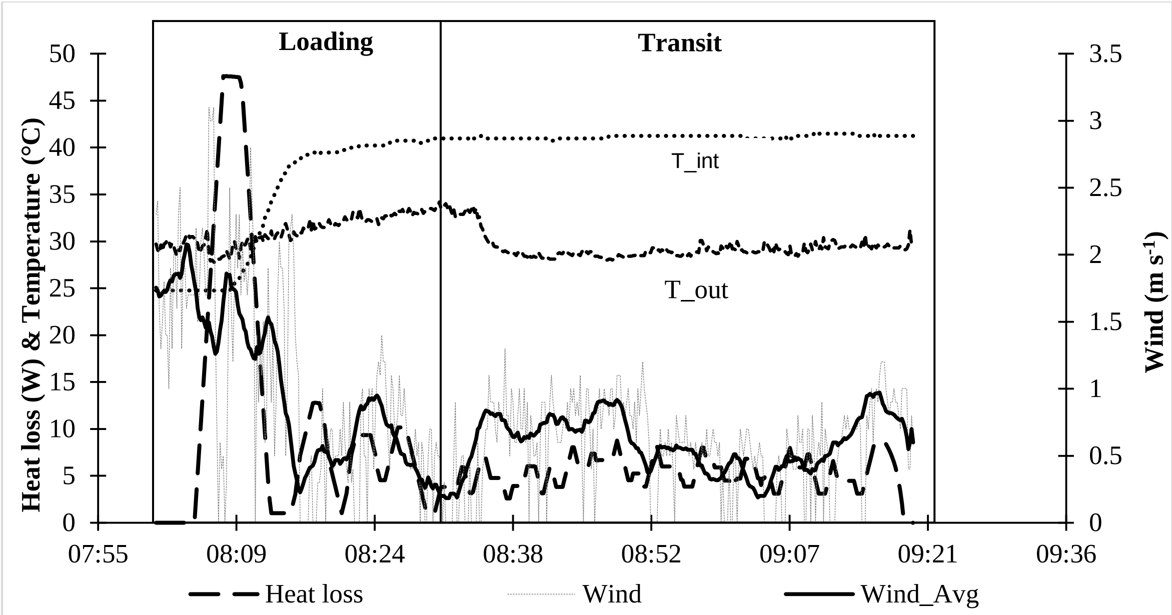


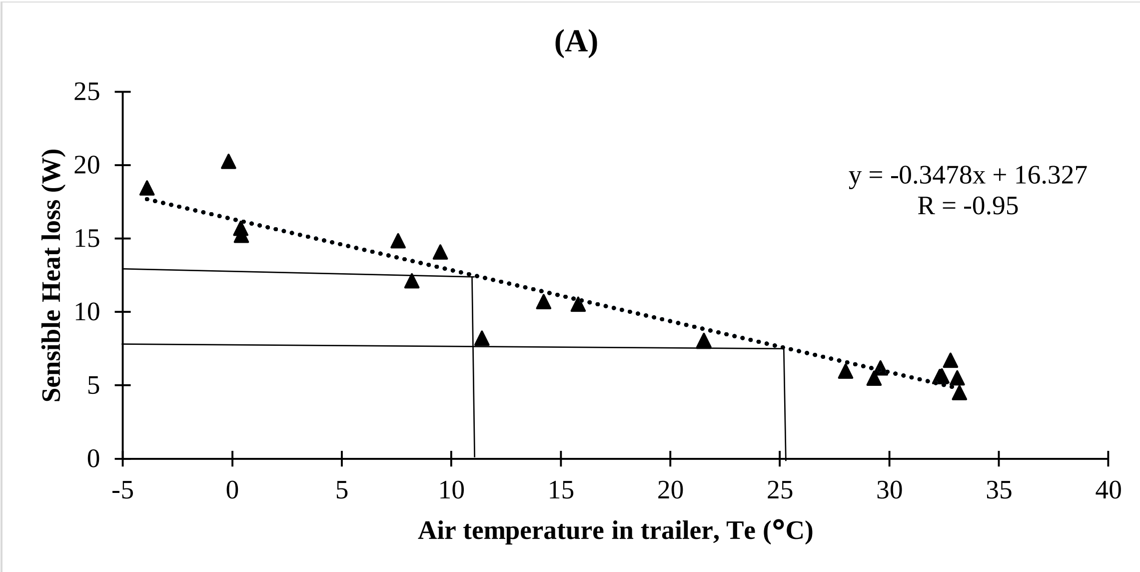
Figure 4.17: Heat loss, the air temperature in the trailer (Te), and the wind during a summer trip for one of the electronic chicken (Power switched on at 08:00 h, with loading ending at 08:30 h).

Observed heat loss ranged from 8.2 to 20.3 W on fully boarded trailers, and from 4.5 to 6.7 W on open trailers (Table 4.6). Observed heat loss in holding during winter was slightly lower than that in transit, likely a result of operating supplemental heat in the shed whenever ambient temperature dropped below 4°C. Heat loss from summer trips was less variable than those of winter trips, likely due to the better uniformity of trailer temperature (Table 4.6). The correlation coefficient of -0.95 and -0.90 during transit and holding respectively, significant at 95 % confidence level, depicts a strong linear relationship between heat loss and ambient temperature. As also discussed above, broilers try to maintain the balance between metabolic heat production and heat loss as sensible or latent heat loss. Webster et al. (1993) reported that the thermo-neutral sensible heat production for electronic chickens ranged between 63 – 69 W m^{-2}, equivalent to 7.56 – 8.28 W per chicken. The E-chickens' sensible heat loss values in the current study were around 5 W at 30°C, 9 W at 18°C, and 16 W at 0°C (fig. 4.18). Based on the reported sensible heat loss within the thermo-neutral zone between 3.7 W kg^{-1} (Genc and Portier,

2005) to 5 W kg^{-1} (Gates et al., 1993; Xin et al., 2001), it can be concluded that measured heat loss values between 7.6 – 12.5 W indicates thermal comforting conditions for the averaged weight chickens (2.5 kg). Results of the current study indicate the temperature range of 11.0°C – 25.1°C during transit and 5.3°C – 21.7°C during holding allowed the chickens to regulate heat by their metabolism and stay thermally comfortable. Webster et al. (1993) reported a thermally comfortable range of 6.5°C to 22°C in still air, and 15°C to 26°C when air velocity is 0.5 m s^{-1} for well-feathered broilers.

Heat loss of E-chickens showed a negative correlation with ambient temperature (fig. 4.18). During transit in winter, heat loss values exceeded 12.5 W when ambient temperatures were below 11°C, indicating possible hypothermic conditions for the broilers. On the other hand, during summers the recorded ambient temperature was up to 33°C with corresponding heat loss around 5 W, suggesting that birds either relied more on evaporative cooling or experienced hyperthermic conditions. The fan and mister combination, commonly used in the southern U.S. during loading, could have allowed additional cooling due to surface wetting of live chickens, although not quantifiable by the current surface wrapping method of E-chickens. However, for the holding period, the winter trips were mostly in the thermoneutral zone, but during summer data suggest the hyperthermic conditions during transit. The mild season between winters and summers were the most suitable for broilers as the heat loss values fell within the thermoneutral zone.

In the close confinement of transport modules, heat loss by radiation and conduction are restricted by the proximity of other chickens having similar surface temperatures, leaving convection the dominant pathway of sensible heat loss. The E-chickens located within the modules provided a continuous measure of integrated sensible heat loss. Further, by using the continuous heat loss data, the companies can make necessary instantaneous changes in the management practices for the following trips in the same day to provide broilers with thermally comforting environment. Therefore, certain trends to changes in management practices in each season can be identified and can be utilized by the companies in future live-haul trips, preventing occurrence of dangerous thermal micro-environment on trailers.



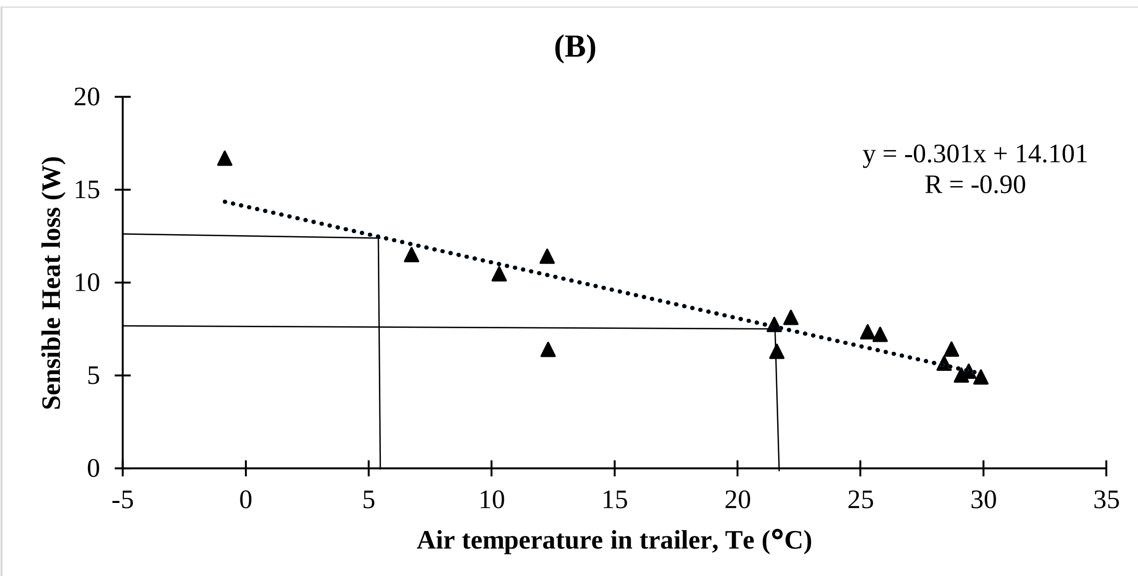


Figure 4.18: Relationship between air temperature in trailer (Te) and sensible heat loss in E-chickens during (A) transit and (B) holding period for commercial live haul trips in the Southern U.S.

4.6 Limitations in data collection

There were some limitations in the current study which are stated below:

- Some data loss occurred due to sensor malfunction due to bird interference or feather blocking vanes (wind), or battery low of E-chickens. Some data from E-chickens were also lost because E-chicken's switch inadvertently turned off due to the impact of module or trailer movement.

- Power of the electronic chickens lasted shorter than expected, causing data loss during the holding period in winters; suggesting the use of bigger batteries for winter runs. However, bigger battery requires a bigger enclosure (or an external battery), and heavier total weight, making it harder to fasten it to the constantly moving modules securely.
- The E-chickens insensitivity to moisture restricted the use of chickens to differentiate the sensible and evaporative heat losses; the effect of different relative humidity during the trip cannot be incorporated in the analysis.
- The data analysis has assumed that the broilers were distributed evenly on trailers; all the trips based on the ventilation configurations were treated uniformly based on the management practices. However, care must be taken to make necessary changes and decisions based on the results discussed.
- During the later trips we realized the need of monitoring wind extensively at all locations on the trailer. Wind data loggers used were few and were not enough to understand the air flow and distribution.

5. Conclusions and Recommendations

Thirty-two commercial live-haul trips were monitored during all seasons in the Southern U.S. Temperature, relative humidity and wind speed were obtained by installing thermal data loggers. Humidity ratio was obtained for all trips, and the characterization of moisture accumulation at all locations on the trailer was done for transit and holding period.

During transit, the Open-Water configuration had the maximum increase in humidity. The mean HR increase-above-ambient for the OW configuration was considerably lower during holding (2.3 g/kg) as compared to transit (3.2 g/kg) due to the artificial water treatment before transit. The midline of middle and back middle rows during transit in one of the trips showed relative humidity near saturation. Thermal cores thus pointed out are thermally stressful to the broilers as the sensible and evaporative heat loss mechanism in the birds gets restricted at such hot and humid conditions. Better control in HR increase-above-ambient was achieved in the holding shed by using fans that were spread uniformly in the holding shed. For Open-No Water trips, both during transit and holding the mean increase in HR were lower (1.7 g/kg and 2.2 g/kg) as compared to the OW trips (3.2 g/kg and 2.3 g/kg). Birds at these thermal conditions with no incidence of relative humidity close to saturation were most likely thermally comfortable under the present practices of the ONW trips both during transit and holding.

Using wind boards did not increase the moisture tremendously during transit. However, during holding, especially for the BD configuration there was a high rise in moisture (3.4 g/kg). The temperature rise experienced was nearly 10°C in the BD configuration during holding. However, no incidence of relative humidity near saturation was recorded in this study, suggesting no high threat conditions observed. Comparing the BW and BD configuration during transit, the mean increase in HR was almost identical, the temperature however increased slightly more in the BW configuration (12°C) as compared to the BD configuration (10.5°C). Overall, the boarded configurations (BS, BD, and BW) showed high variability along different rows of the modules during transit and in holding.

The middle row of the modules over all configurations had the most increase in the HR i.e. 2.45 g/kg during transit, suggesting the moisture accumulation in the middle portion of the trailer during transit. A similar trend was observed for the holding period where the middle and back middle modules had the high values as compared to the other three row locations. The midline of each module had higher HR increase-above-ambient as compared to exteriors, both during transit and holding. Combining the above two trends in the humidity variations, there seems to be a thermal core right at the center of the trailer both during transit and holding. The air flow was restricted by the birds towards the middle of the modules as compared to the exterior portions. The results of our study suggested no clear inlet and outlet on live-haul chicken trailers.

The heat indexes analysis was carried out for a summer trip in June (48 min transit and 152 min holding). The wind data were gathered along with temperature and humidity, the exterior and midline thermal condition comparison was made. AET values suggested dangerous conditions for the broilers throughout the trailer while the THVI values found normal conditions near to upper threshold of the normal zone of homeostasis as defined by Tao and Xin (2003).

It is important to understand that the ventilation is the only solution for better control of thermal environment on board and thus the effective way to enhance the well-being of the birds during the pre-slaughter transport.

We also constructed four electronic chickens that were fabricated with a surface area of 0.121 m^2. Laboratory tests showed that the four instrumented chickens display similar power consumption behavior with good repeatability. Power consumptions are negatively correlated to temperature and positively correlated with the wind. Electronic chickens were installed on eight commercial live haul trips during winter, summer and mild transition season. The heat loss collected in the field validated those from the laboratory tests. Field data from E-chickens showed possible hyperthermic conditions for broilers on board when the temperature was above 25.1°C for transit and 21.7°C for holding, or hypothermic when the temperature was below 11.0°C for transit and 5.3°C for holding. E-chickens were useful in detecting stress condition and can be used in future data acquisition by the researchers. While transporting, the electronic chickens can quantify the sensible heat loss under different environmental conditions, which are affected by various management practices. Further, by combining with the continuous monitoring of temperature on the trailer, the calculated heat loss will allow quantitative analysis to suggest different levels of physiological stress imparted on the broilers. E-chickens can be used as a warning system which will not only help enhance the well-being of the broilers but also lead to a reduction in economic losses. The E-chickens are highly portable and can be used in extremely harsh conditions; giving the advantage to get the data which was otherwise difficult to gather without disturbing live chickens physically and psychologically. E-chickens could well be utilized in understanding the variations of the wind and other thermal parameters like temperature and humidity on the trailers and its effects on the birds. Work could also be done in better utilization of this tool in various sectors which involves thermal stress issues for chickens.

Overall, we were able to identify regions of thermal discomfort for the broilers on the trailers during transit and holding. Different management practices were compared based on the moisture accumulations and suggestions were provided to improve the well-being of the birds.

More research, especially in the field of air distribution on the loaded trailer are needed, to be more specific and confident in pointing out the areas of thermal-discomfort to the birds.

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Appendices

A. Mean humidity ratio increase-above-ambient comparison for transit and holding

Table A.1: Mean humidity ratio-increase-above ambient in commercial trailers during transit period for midline and exterior of modules in every location on trailer.

Configuration	**Open-Water**		**Open-No Water**		**Boarded-Single**		**Boarded-Double**		**Boarded-Wrapped**	
Mean Ambient humidity ratio	15.96 (2.57)		12.87 (5.06)		5.31 (2.12)		2.53 (1.54)		1.83 (1.10)	
	Humidity ratio increase-above-ambient (g/kg)									
Location	**Midline**	**Exterior**	**Midline**	**Exterior**	**Midline**	**Exterior**	**Midline**	**Exterior**	**Midline**	**Exterior**
Front	2.66 *abcde*	2.89 *abc*	1.66 *cdefgh*	1.46 *defgh*	1.86 *bcdefgh*	1.64 *defgh*	3.56 *ab*	1.89 *bcdefgh*	2.04 *abcdefg*	2.17 *abcdefg*
Front Middle	3.56 *ab*	3.93 *ab*	2.00 *bcdefgh*	1.34 *efgh*	1.47 *defgh*	1.32 *fgh*	1.48 *defgh*	1.39 *efgh*	2.48 *abcde*	2.31 *abcdef*
Middle	3.95 *ab*	3.59 *ab*	1.99 *bcdefgh*	1.33 *efgh*	2.33 *abcde*	1.30 *fgh*	2.80 *abcd*	2.37 *abcde*	3.89 *ab*	2.67 *abcde*
Back Middle	2.57 *abcde*	2.60 *abcde*	2.03 *abcdefg*	2.01 *abcdefgh*	1.37 *efgh*	1.38 *efgh*	3.68 *ab*	2.67 *abcde*	0.98 *h*	2.89 *abcd*
Back	2.78 *abcd*	4.10 *a*	1.48 *defgh*	1.79 *bcdefgh*	1.53 *defgh*	1.22 *gh*	2.20 *abcdef*	1.89 *bcdefgh*	1.93 *bcdefgh*	2.54 *abcde*

* Means having the same letter are not significantly different; all values except for BW-back middle-midline have p-value < 0.05

Table A.2: Mean humidity ratio increase-above-ambient in commercial trailers during holding period for midline and exterior of modules in every location on trailer.

Configuration	**Open-Water**		**Open-No Water**		**Boarded-Single**		**Boarded-Double**	
Mean Ambient humidity ratio	16.90 (2.94)		14.14 (4.88)		5.45 (1.92)		2.63 (1.12)	
	Humidity ratio increase-above-ambient (g/kg)							
Location	**Midline**	**Exterior**	**Midline**	**Exterior**	**Midline**	**Exterior**	**Midline**	**Exterior**
Front	2.36 *abcde*	1.86 *de*	2.20 *abcde*	2.24 *abcde*	3.04 *abcde*	2.13 *bcde*	4.38 *a*	3.04 *abcde*
Front Middle	3.30 *abc*	2.24 *abcde*	2.06 *bcde*	1.96 *bcde*	2.26 *abcde*	2.49 *abcde*	2.94 *abcde*	2.40 *abcde*
Middle	2.56 *abcde*	2.58 *abcde*	2.04 *bcde*	2.07 *bcde*	3.19 *abcd*	2.70 *abcde*	3.72 *ab*	4.11 *ab*
Back Middle	2.39 *abcde*	2.19 *bcde*	2.02 *bcde*	2.59 *abcde*	4.11 *ab*	2.72 *abcde*	3.89 *ab*	3.74 *ab*
Back	2.30 *abcde*	1.72 *e*	2.36 *abcde*	2.32 *abcde*	1.92 *cde*	1.96 *cde*	3.06 *abcd*	3.04 *abcde*

* Means having the same letter are not significantly different; all values except for BW-back middle-midline have p-value < 0.05

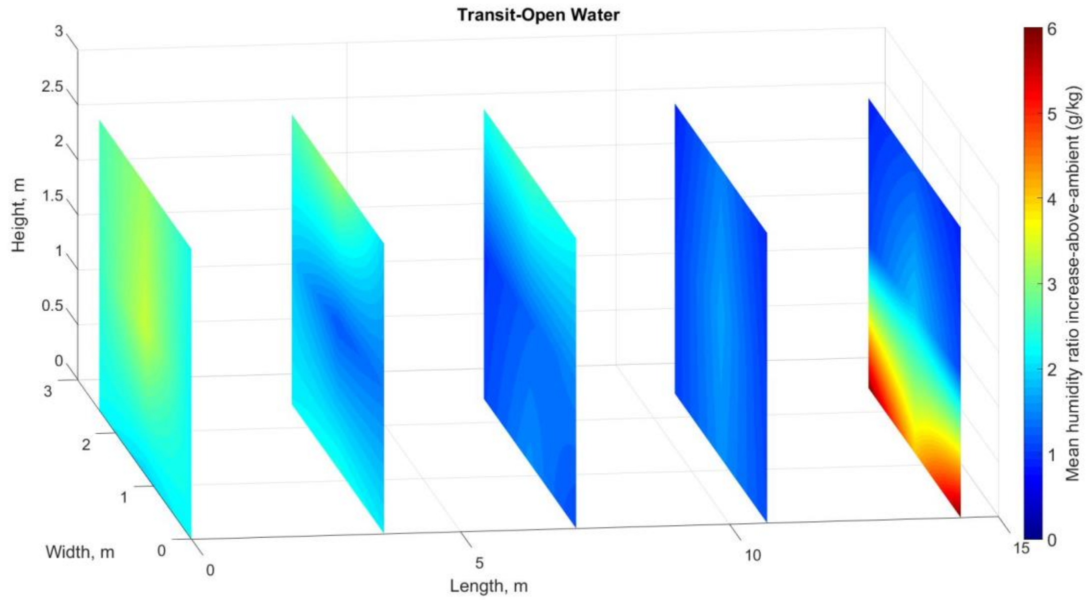

Figure A.1: Distribution of HR increase-above-ambient on the trailer during transit of Open-Water trips.

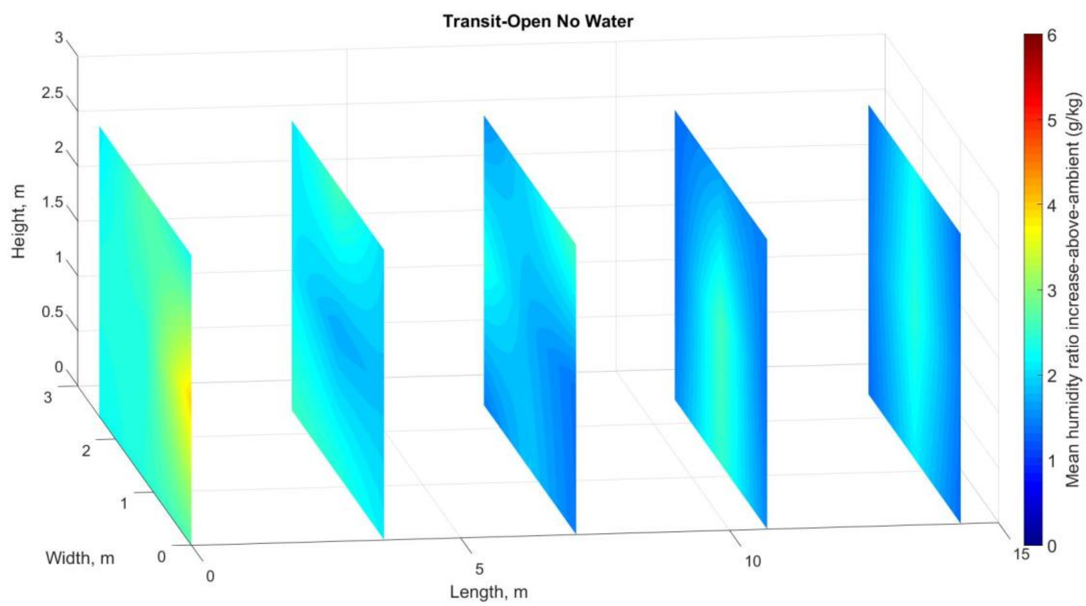

Figure A.2: Distribution of HR increase-above-ambient on the trailer during transit of Open-No Water trips.

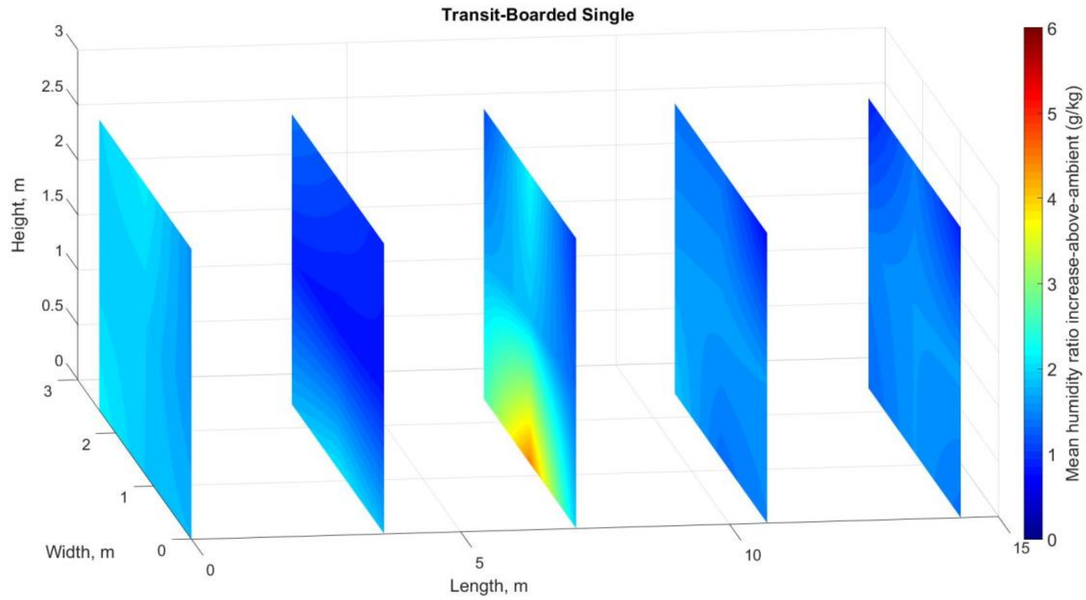

Figure A.3: Distribution of HR increase-above-ambient on the trailer during transit of Boarded-Single trips.

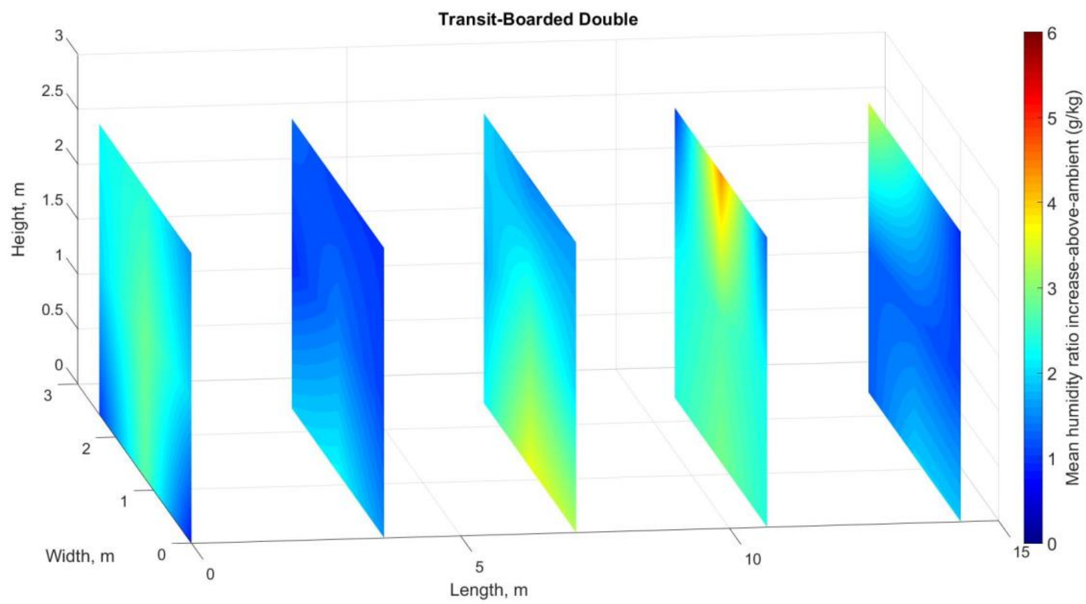

Figure A.4: Distribution of HR increase-above-ambient on the trailer during transit of Boarded-Double trips.

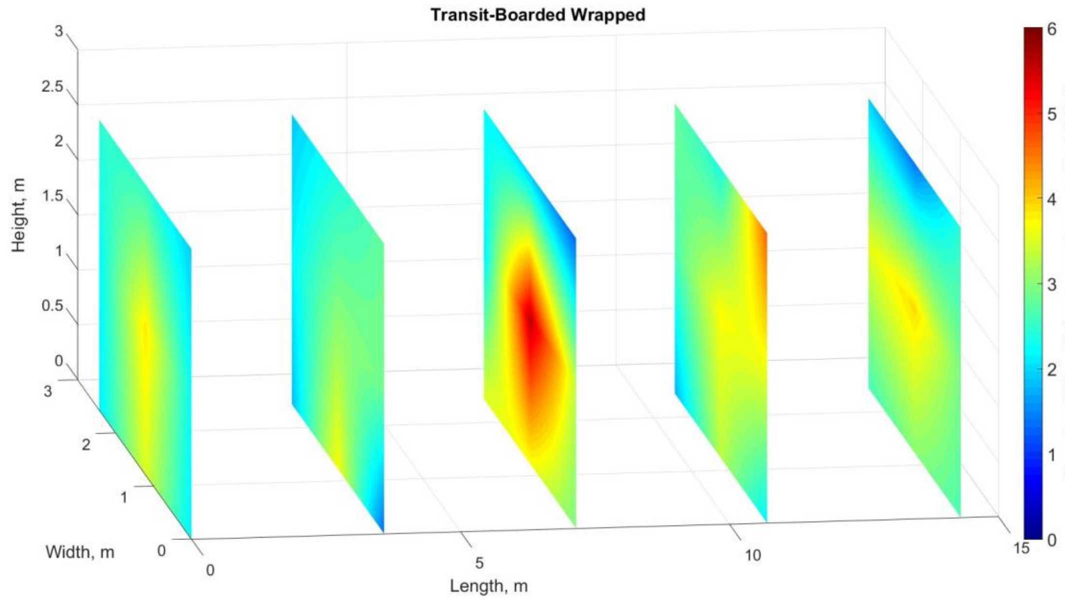

Figure A.5: Distribution of HR increase-above-ambient on the trailer during transit of Boarded-Wrapped trips.

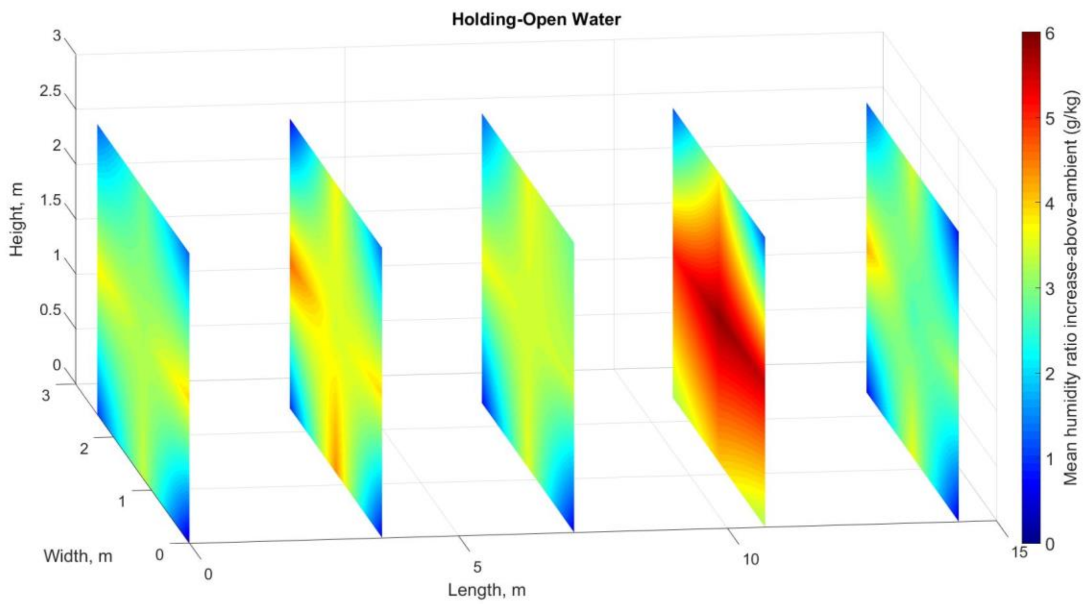

Figure A.6: Distribution of HR increase-above-ambient on the trailer during holding of Open-Water trips.

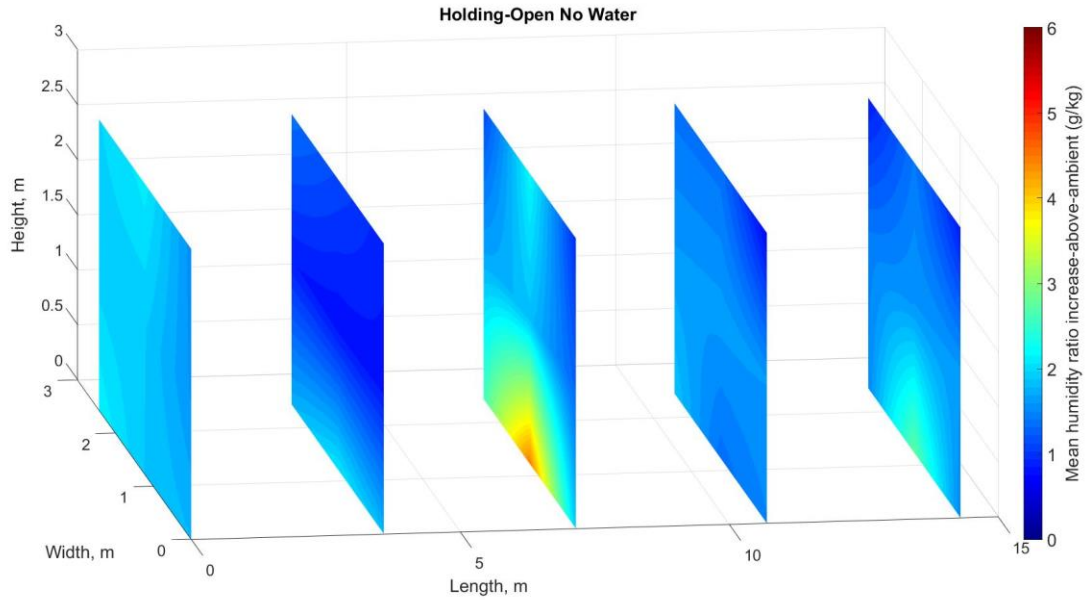

Figure A.7: Distribution of HR increase-above-ambient on the trailer during holding of Open-No Water trips.

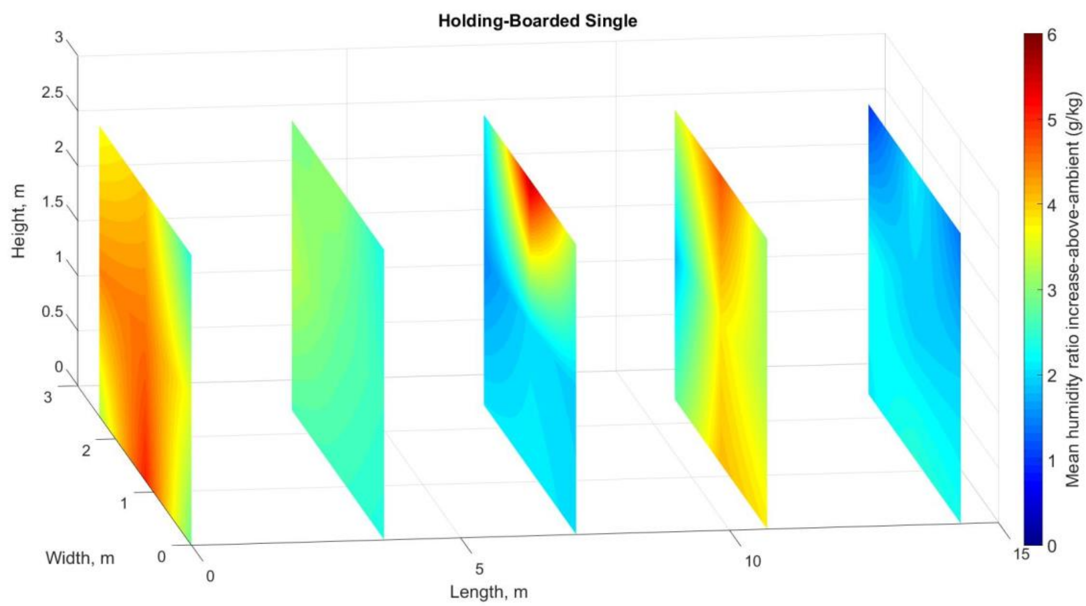

Figure A.8: Distribution of HR increase-above-ambient on the trailer during holding of Boarded-Single trips.

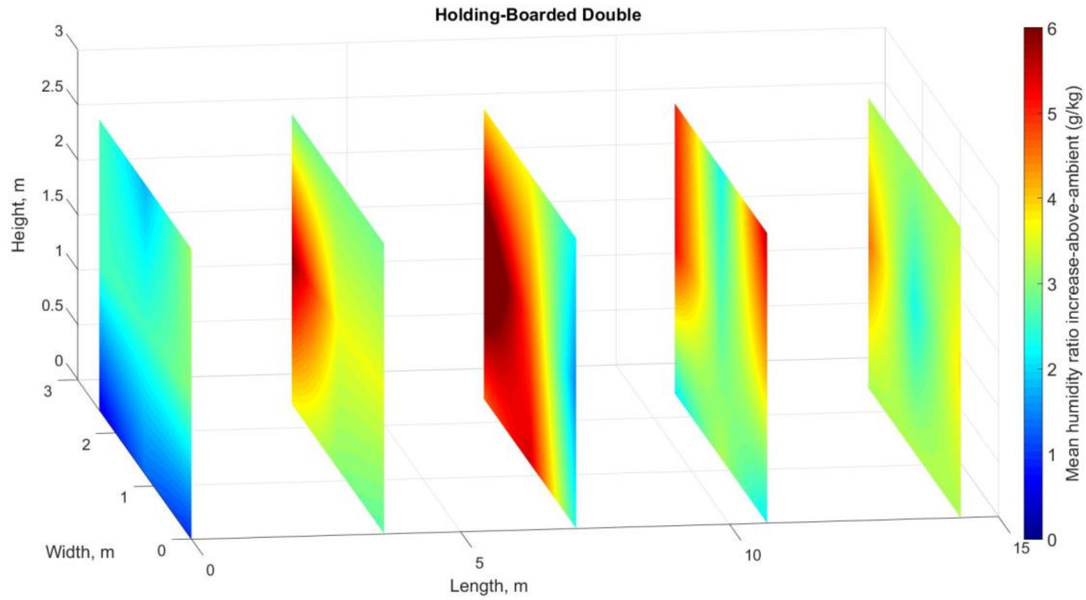

Figure A.9: Distribution of HR increase-above-ambient on the trailer during holding of Boarded-Double trips.

B. Research compliance approval letter

UNIVERSITY OF ARKANSAS

Office of Research Compliance

MEMORANDUM

TO: Dr. Yi Liang

FROM: Craig N. Coon, Chairman
Institutional Animal Care and Use Committee (IACUC)

DATE: 12-8-14

SUBJECT: IACUC APPROVAL
Expiration date: January 1, 2018

The Institutional Animal Care and Use Committee (IACUC) has APPROVED your protocol 15026: *'Characterizing Thermal micro-Environment during Poultry Transportation'* to begin January 2nd, 2015.

In granting its approval, the IACUC has approved only the information provided. Should there be any further changes to the protocol during the research, please notify the IACUC in writing (via the Modification form) prior to initiating the changes. If the study period is expected to extend beyond January 1, 2018 you must submit a new protocol prior to that date to avoid any interruption. By policy the IACUC cannot approve a study for more than 3 years at a time.

The IACUC appreciates your cooperation in complying with University and Federal guidelines involving animal subjects.

CNC/aem

cc: Animal Welfare Veterinarian

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