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Engineering and design of vehicles for long distance road transport of livestock (ruminants, pigs and poultry)

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Summary

During road transportation, livestock are subjected to a number of concurrent potential stressors that can increase mortality and morbidity and compromise welfare status and production efficiency. A major concern is the thermal micro-environment within the vehicle with both heat stress and cold stress constituting major problems. It is possible to mitigate the effects of external climatic conditions by improving vehicle design and operation using engineering solutions that match 'on-board' environmental conditions with the biological requirements of the animals. This review describes an investigative approach that targets four elements. These are the thermal conditions on commercial transport vehicles under a range of climatic conditions, the 'thermal comfort zones' or target conditions for different livestock species, the heat and moisture loads upon vehicles that must be dissipated and the thermodynamic characteristics of animal transport vehicles that affect the design of mechanical or active ventilation systems able to function at maximum efficiency under everyday commercial conditions. Results of research around these four elements can provide the sound scientific basis for improved vehicle design and operation and for legislation and codes of practice aimed at optimising animal welfare and productivity in relation to transportation of livestock on journeys of both long and short duration.

Keywords

Animal, Cattle, Livestock, Pigs, Poultry, Road, Sheep, Stress, Temperature, Transport, Ventilation, Welfare.

Design e progettazione dei veicoli per il trasporto a lunga distanza su strada di bestiame (ruminanti, suini e pollame)

Riassunto

Nel trasporto su strada il bestiame è soggetto ad un numero di fattori concomitanti di stress che incrementano la mortalità e la morbilità e che compromettono il benessere e l'efficienza produttiva. Problema ancor più importante è il microclima all'interno del veicolo e lo stress da calore e da freddo che ne derivano. E' possibile mitigare gli effetti delle condizioni climatiche esterne sul veicolo migliorando il design e l'efficienza del mezzo dotandolo di un sistema che adegui le condizioni ambientali interne alle necessità biologiche degli animali. Questo studio illustra il metodo che ha portato all'individuazione di quattro problematiche. Esamina le condizioni climatiche sui veicoli per il trasporto commerciale, le "thermal confort zones", quindi la creazione di condizioni climatiche mirate per ogni specie diversa, l'esigenza di disperdere il calore e la condensa che si formano nei veicoli durante il trasporto, le caratteristiche termodinamiche dei veicoli destinati al trasporto di animali e l'efficienza del loro sistema di aerazione nonché

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l'eventuale presenza di un sistema di ventilazione capace di lavorare alla massima efficienza nel trasporto commerciale quotidiano. I risultati delle ricerche su queste quattro problematiche possono fornire le basi scientifiche per migliorare il design dei veicoli e la relativa normativa e i manuali pratici volti a ottimizzare il benessere animale e la produttività nel trasporto di bestiame sia a breve sia a lunga distanza.

Parole chiave
Aerazione, Animale, Benessere, Bestiame, Bovini, Pollame, Ovini, Strada, Stress, Suini, Temperatura, Trasporto.

General introduction

The road transportation of livestock continues to be a topic of great public concern and an issue of major political importance. The conditions under which animals are transported, rather than the act of transportation *per se*, may induce marked physiological stress which, in turn, will compromise the welfare of the animals in transit, increase losses through elevated mortality, morbidity and decreased product quality and increased waste and, overall, may reduce production efficiency. There are many concurrent stressors that may be imposed during transportation and the effects of these challenges may be additive or multiplicative in the sense that the detrimental effects of a given stressor may be exacerbated or enhanced by simultaneous exposure to another. The deleterious effects of these stressors upon the welfare of the animals in transit and upon production parameters may increase with journey duration. It may be argued, in general, that long distance transport may potentially constitute a greater risk to animal well-being than journeys of short duration.

Of the stressors that may be encountered during journeys of all durations, the thermal micro-environment of the 'transport space', 'transport container' or 'bio-load' is recognised as the major threat to animal well-being and health. Concerns relating to animal transport in general and to the thermal conditions to which the animals are exposed have led to the development and implementation of regulations, legislation and codes of practice in a number of countries and trade areas around the world that seek to impose limits on journeys times, stocking densities in transit and thermal conditions inside the vehicle. It is essential that such regulations and codes are based upon sound fundamental and relevant scientific principles and research.

Relevant research can examine the biological or physiological requirements of the animals in transit and relate these to the conditions potentially encountered. The results then may not only inform the development of appropriate legislation and advice but can also form the basis of sound strategies for the minimisation of physiological stress in transit by matching the on-board environments or conditions to the animals' need or requirements. Frequently, solutions to the problems of animal transport will involve both improved engineering and design of vehicles and transport containers and recommendations for improved transport practices and procedures. Appropriate research can identify and determine the 'thermal comfort zones' in transit for different species of livestock, characterise the factors that determine the 'on-board' thermal micro-environment, identify methods of controlling the thermal conditions in the vehicle within the prescribed range for each species and provide the sound scientific basis for appropriate legislation to ensure the implementation of the engineering solutions for maintaining animals within the biological optimum thermal environment in transit.

This review addresses the application of a physiological modelling-based approach to the provision of engineering solutions to the major problems encountered during the transport of livestock. Particular emphasis is placed upon the thermal micro-environment on commercial vehicles and on journeys of long duration. In Europe, longer journeys are defined as being of a duration that exceeds 8 h and may last for periods of up to 19-29 h dependent upon the species and age of the animal. Primarily, the information in this review relates to potential heat stress on longer journeys as this is regarded as a major cause of reduced welfare in transit. However, it must be recognised that cold stress is also a significant problem and that this must be addressed by the application of similar approaches and methods. Examples of research that has provided valuable inputs to yield engineering solutions have been included for pigs and sheep and, to a lesser extent, for calves. All of these species can be exposed to a range of hostile conditions on journeys of both short and long duration. Whilst most poultry transportation involves journeys of relatively short duration, engineering solutions developed in this sector are included as they formed the valuable foundation of subsequent studies in red meat species.

Animals and the transport thermal micro-environment

It has been reported that the transport of farm animals involves a number of stressful elements (5, 16, 17, 45, 46, 47, 53), which individually or in combination may compromise welfare, reduce meat quality and increase mortalities (6, 31, 33, 36, 47). Furthermore, concurrent stressors can affect animals in transit in various ways (17, 22, 30, 35, 45, 46, 47).

The thermal micro-environment within the transport container poses the greatest threat to the welfare and well-being of animals (7, 36, 39, 43, 44). Adverse thermal conditions resulting in either heat or cold stress reduce the welfare of animals through overt tissue damage or injury and increase mortality in transit (19, 20, 36, 37, 38, 41, 42, 47). Special attention should be paid to the incidence of increased thermal loads and heat stress as this is a recognised cause of transport stress in all world climates.

The thermal micro-environment in transport containers or vehicles may be complex and result from the interactions of several factors. These factors include the external climatic conditions, heat and water production of the animals, ventilation regimes, distribution and flow rates and any additional external sources of heat and/or moisture. The metabolic heat and water production of animals in transit is a major determinant of the 'on-board' thermal environment and this can be of vital importance if external conditions and/or ventilation are likely to precipitate heat stress (24, 25, 26, 27, 28). The carriage of large numbers of closely packed animals will result in the addition of a great amount of heat and water vapour inside of the vehicle during transportation. In warm weather and an increased temperature and humidity within the vehicle, the animals will respond by increased evaporative water loss through panting or sweating. The net effect is the creation of a hot, humid transport micro-environment in close proximity to animals which imposes ever increasing demands upon their thermoregulatory and other homeostatic systems (23, 24, 25, 26, 27).

Animals maintain their deep body temperature relatively constant by altering rates of heat production and heat loss to optimise heat storage. Heat loss may be regulated by animals through changing posture and peripheral insulation (sensible heat loss) or by adjusting the rate of evaporative or latent heat loss from the respiratory tract via panting and/or from the skin via sweating or transcutaneous water loss. Increased thermal loads on animals require increased thermoregulatory activity and heighten the risk of changes in deep body temperature. Thus, heat stress may be characterised by the associated extent of the increase in thermoregulatory effort and the degree of thermoregulatory success.

Accordingly, it can be proposed that the ideal thermal micro-environment during transport is one that requires minimal thermoregulatory effort and results in maximum thermoregulatory success. These conditions should allow optimal sensible and latent heat exchange between the animal and its immediate environment. They would also require minimal adjustment of heat production by an animal and therefore pose minimal threat to homeothermy. Optimal 'on-board' thermal environments require efficient heat exchange and this might be achieved by controlling imposed heat loads with appropriate ventilation strategies (24, 25, 26, 27, 28, 29, 37, 39, 40, 41, 42, 43, 44).

Legislation and regulations relating to thermal conditions during the transport of livestock

Many countries developed and implemented legislation or regulations and codes of practice relating to the transportation of animals during the last two decades of the 20th century. The major purpose of these rules has been to improve or optimise the welfare of animals in transit. The requirements of such legislation and the basis for the development of relevant regulations have been discussed widely (7, 10, 13, 15, 49, 50). In Europe, the introduction and adoption of the Directives and Council Regulations (10, 12, 13) were implemented within the United Kingdom in the Welfare of Animals (Transport) Order 1997 (1), which was further revised under the Welfare of Animals (Transport) (Amendment) Order 1999 (2). In January 2007, the introduction throughout the European Union member states of Council Regulation (EC) 1/2005 has seen further modification of the rules regulating animal transport in member states (14). Particular emphasis has been placed upon the control of temperature in transit and the means of forced or mechanical ventilation through which this might be achieved. This regulation, which applies across all 27 member states, aims to improve animal welfare through raising transportation standards (14). The regulation covers the transport of all live vertebrate animals that takes place in connection with an economic activity. Within the United Kingdom, this regulation has been implemented as the Welfare of Animals (Transport) (England) Order 2006, with parallel legislation in Scotland, Wales and Northern Ireland (3). The regulation stipulates general conditions for the transport of animals to ensure their safety and well being. It also specifies requirements for vehicles used to transport animals, with vehicles used for longer journeys (over 8 h in duration) being required to meet additional criteria. An inspection and approval scheme is in place to check vehicle compliance for the latter group of vehicles.

Thus, Council Regulation (EC) 1/2005 states that transport practices should ensure that:

- 'sufficient ventilation shall be provided to ensure that the needs of the animals are fully met taking into account in particular the number and type of the animals to be transported and the expected weather conditions during the journey. Containers shall be stored in a way which does not impede their ventilation'
- to reduce solar gain on vehicles for all long journeys, 'the means of transport shall be equipped with a roof of light colour and be properly maintained'
- 'ventilation systems on means of transport by road shall be designed, constructed and maintained in such a way that, at any time during the journey, whether the means of transport is stationary or moving, they are capable of maintaining a range of temperatures from 5°C to 30°C within the means of transport, for all animals, with a ±5°C tolerance, depending on the outside temperature'
- 'the ventilation system must be capable of ensuring even distribution throughout with a minimum airflow of nominal capacity of 60 m^3/h/KiloNewton (KN) of payload. It must be capable of operating for at least 4 h, independently of the vehicle engine'.

In the SI system, the mass unit is the kg and since the weight is a force [mass × acceleration], the weight unit is the Newton (N). For a body with 1 kg mass, weight can then be expressed as:

$w = 1\ (\text{kg})\ 9.807\ (\text{m/s}^2) = 9.807\ (\text{N})$

where:

9.807 (m/s^2) = standard gravity close to earth in the SI system.

As a result:

- a 9.807 N force acting on a body with 1 kg mass will give the body an acceleration of 9.807 m/s^2
- a body with mass of 1 kg weighs 9.807 N.

A KiloNewton is therefore 1 000 N.

It is not certain that the thermal limits prescribed in such legislation are entirely appropriate for all livestock likely to be transported or indeed for livestock that may be in differing physiological states. Unpublished studies by the authors indicate that the upper limits for temperature in the European Union regulations may be too low for pigs (and indeed calves and lambs) bred and reared in southern European climates and therefore fully acclimatised to elevated thermal loads. Further work is necessary in this area to better define thermal comfort ranges for acclimated and non-acclimated animals

Meeting the legislative requirements and the needs of the animals

To design and implement the engineering improvements necessary to optimise animal welfare in transit through environmental control strategies it is necessary to:

- define the thermal comfort zones for each species (and age/size) of animal for transportation; this means characterising the thermal loads that impose minimal thermal stress
- identify and quantify the sources of heat and moisture production in commercial animal transport vehicles
- characterise the ventilation regime in commercial vehicles and relate this to the thermal micro-environments and their distribution.

Physiological models and thermal limits

Appropriate ventilation regimes and rates for animal transport vehicles can be specified to reduce thermal gradients between external conditions and the interior of animal transporters and to dissipate any heterogeneous distributions of internal thermal loads. The physical principles involved in such calculations can be applied to any range of environmental temperatures and humidities and can be employed to achieve any set of target conditions. It is, of course, essential to precisely define the optimum (target) thermal conditions for the transportation of each species and identify the acceptable ranges and limits of the temperatures and humidities to which the animals might be exposed in transit, taking full cognisance of possible journey durations. This may be described as defining the 'thermal comfort zones' for a particular species, age or sex of animal. These objectives may be achieved by means of 'physiological stress response modelling' (37, 39, 40). This approach involves the measurement of physiological responses of animals to quantified individual stressors typical of those encountered during transport or appropriate stressor combinations.

Modelling studies may be initially undertaken in laboratory conditions where variables other than those subject to analysis can be accurately controlled. This approach is based on control theory and involves the measurement of homeostatic success and effort in response to graded challenges or stressors. The degree of displacement of a physiological 'controlled variable' from its 'set point' is inversely proportional to homeostatic success and the magnitude of any adaptive response reflects the extent of the homeostatic effort.

The physiological responses or variables selected for inclusion in any model should reflect the entire range of homeostatic systems that may be affected by 'transportation stress'. In this way, the model will be 'holistic' in that it will integrate the spectrum of physiological responses to an individual stressor or complex set of conditions (7, 39). This 'modelling' approach has allowed definition of thermal comfort zones for broilers in transport crates in commercial transport conditions (7, 39) and the application of the findings to an improved ventilation system for broiler transport vehicles (25, 26, 27). Physiological response modelling can provide the data necessary to specify acceptable ranges and limits for temperatures and humidities within animal transport vehicles and therefore acceptable temperature and humidity 'lifts' above external conditions. Studies have now been completed defining thermal comfort zones for broiler chickens, pigs and calves.

Transport environments and ventilation

Research into livestock vehicles and studies on the effects of transport on the animals *per se* have generally focused on naturally ventilated vehicles. Passive or natural ventilation is very variable, however, and dependent primarily on vehicle movement and wind speed and direction. Little control is available over such ventilation regimes other than opening and closing ventilation apertures, which requires the vehicle to stop for the driver to make adjustments that he perceives to be appropriate. Accordingly, there is scope for inadequate ventilation in the summer or excessive ventilation in the winter.

Some research has addressed the use of mechanical ventilation on livestock vehicles (32, 33, 34, 52). This has investigated the effects on animals of a given ventilation system rather than defining the requirements for such a system. Mechanical ventilation was expected to limit the extreme values of temperature and humidity but this expectation was not seen. Description of ventilation systems in these studies suggests that they may not have been optimally designed to ensure a defined air stream over all the animals, with the consequent shortcomings.

Studies on the air movement around vehicles have usually concentrated on the determination of methods for reducing aerodynamic drag (21, 48). Wind tunnel modelling has been employed to try to improve the internal environment particularly for reducing ingress of aerial pollutants such as dust (51). More recently, aerodynamics and ventilation characteristics of poultry transport vehicles with full-scale studies and scale model investigations in wind tunnels have been investigated (4, 9, 18).

Vehicle ventilation regimes

Two ventilation regimes in which the air movement through a vehicle should be considered are passive or natural and active or mechanical ventilation. Passive ventilation is the situation that exists on most standard transport vehicles. Air exchange within the container is driven by virtue of thermal buoyancy, movement of the vehicle itself and by the prevailing wind. With active ventilation, powered fans are fitted to the vehicle to provide air movement at all times.

Passive ventilation

The external pressure field around a moving vehicle has been reported (18) and modelled (4, 9) and determines the internal air flow patterns in a vehicle. A typical livestock transporter has a solid headboard and standard side grille vents. As the vehicle travels down the road, air passing over the front edge of the container separates from the vehicle and creates a region of low pressure (suction). The air flow re-attaches along the length of the vehicle and by the rear grilles where the magnitude of suction is much less than at the front grilles. The net effect of this pressure field is that air tends to enter at the rear grilles, move forward within the container over the animals and leave through the front grilles. Holes drilled through the front headboard will allow air to enter the container but the resulting air stream will tend to be drawn out through the front grilles. This air stream will not travel through the length of the vehicle and may, therefore, reduce ventilation efficiency.

When a vehicle is stationary, the external pressure field associated with vehicle movement disappears and internal airflows are driven primarily by the prevailing wind. There is little control over the airflow through the container and the prevailing wind direction will dominate the airflow pattern on windy days. On occasions when there are strong crosswinds, the resultant airflow will be across the vehicle. Parking vehicles at right angles to the wind direction can be used to allow airflow amongst the animals during hot weather.

Active ventilation

Fans that provide air movement within the container can ensure that adequate ventilation is provided for all the animals throughout the entire transit period, including stationary periods. The nature of the internal airflow will be determined by the location of air inlets and outlets and the differential pressure between them. When active ventilation is employed, extracting air from the container is preferable to trying to blow air into the container. This removes the possibility that air jets in close proximity to animals will be detrimental to their welfare. Airflows must pass over all the animals to afford heat exchange between them and the air stream.

An optimal design for an active ventilation fan system will have extraction fans mounted at regions of low pressure to enhance their performance when the vehicle is moving, and have air inlets and outlets at locations which will ensure that the ventilating air passes over all the animals within the container. Such a system design lends itself to automated control.

Heat and moisture production of animals in transit

To calculate ventilation requirements, it is necessary to prescribe the target thermal conditions and to determine the heat and moisture loads that must be dissipated to achieve control within the defined optimal envelope. The heat and moisture production of the animals on-board the vehicle are major contributors to the vehicle thermal micro-environment. There are published equations (8) which allow the theoretical heat production of animals to be estimated. Using these equations, typical theoretical values of total heat production can be calculated. For example, cattle of 500 kg produce 560 W per animal; pigs of 100 kg, 160 W per animal; sheep of 30 kg, 78 W per animal. On a typical livestock transporter, with a deck length of 13.6 m and stocked at recommended stocking densities, the total amount of heat produced per deck is: cattle 13 400 W, pigs 11 500 W and sheep 8 000 W.

The only published data based on field measurements rather than predictive models for animals under transport conditions is that for broiler chickens (23). These data have been employed in the development of a fully controlled mechanically ventilated broiler transport vehicle (26, 27). Similar information for the red meat species (cattle, sheep and pigs) has previously been unavailable. Studies by the authors have utilised a purpose-built research vehicle, capable of transporting large groups of animals in commercial conditions and deriving the heat and moisture losses from animals in transit. The transporter is equipped with fully controlled mechanical ventilation that ensures an adequate airflow over all the animals throughout the entire transit period, irrespective of vehicle movement.

Mechanical ventilation – a research vehicle

The research vehicle has a mechanically ventilated lower deck featuring four fans, one pair on each side of the vehicle, located at the front side of the container. These fans extract air from within the container and are located where regions of low external pressure develop on the moving vehicle (4, 9, 18). To operate on the vehicle 24 V DC powered axial flow fans were selected each with a nominal maximum throughput of 0.5 m^3/s. The two rear grilles, one on each side of the vehicle, were used as air inlets, each with an area of 0.76 m^2. All the other grilles along the side of the vehicle were kept closed. If the fans are operated at maximum speed then the average inlet air speed will be 1.32 m/s. The static pressure drop across the fans during operation was typically 10-20 Pa. This regime results in air being drawn in at the rear of the vehicle, moving forwards over all the animals and being extracted through the fans at the front sides of the container.

Combined temperature/relative humidity sensors were mounted near each rear air inlet and by each of the ventilating fans. The rear sensors were guarded mechanically to protect them against interference by the animals. In addition to the temperature and humidity measurements, levels of carbon dioxide were monitored at the inlet and outlet to provide information on the generation of carbon dioxide by the group of animals.

Air flow rate was determined by measuring the pressure drop across the extraction fans and relating this to calibration curves from laboratory testing of the fans under equivalent conditions. For logistic reasons, including gross vehicle weight restrictions, the upper deck was not used to transport animals in these studies.

Experimental data collection

Data were collected during commercial journeys moving pigs and sheep from farm sites to abattoirs at commercial stocking densities. For slaughter weight pigs (90-100 kg live weight) there were 75 pigs on each deck and with lambs (42-44 kg live weight) there were 84 sheep on each deck. Details of the measurement sensors, on-board data recording system and fan specification and control system have been fully reported previously (24, 25).

Heat and moisture production of animals in transit

Given that the ventilation on the lower deck is fully controlled, the entire deck can be considered as a calorimeter. This facility enables the measurement, under true commercial conditions, of the heat and moisture generated by animals during transport. Heat and moisture released by the animals into the ventilating air stream causing changes in the temperature and humidity that can be measured. In addition, the carbon dioxide production of the animals can also be determined and used to determine the metabolic heat production (23, 24, 25, 26, 27).

In these studies, the following points are recognised:

- changes in moisture content of the air between inlet and outlet includes water released from urine and faeces
- changes in the thermal condition of the air between inlet and outlet account only for heat released to the ventilating air
- metabolic heat production assumes a respiratory quotient (RQ) appropriate for a fasted animal (RQ=0.7).

A mathematical model is currently being developed which considers alternative sources of heat gain (e.g. solar gain) and heat loss (e.g. conduction through the structure of the vehicle) which will improve the analysis of these and future data.

Pigs

The changes in metabolic heat production and moisture generation for a typical experimental journey are presented in Figures 1 and 2. This example incorporated a deliberate stationary period of 2 h mid-journey. Following loading, there was an initial total heat production of 23 kW (3.4 W/kg), which fell to 9.5 kW (1.4 W/kg) immediately prior to the stop (Fig. 1). During the standing period, heat production rose to 22.3 kW (3.3 W/kg). When the vehicle recommenced moving, the heat production decreased, reaching a final level of 13.7 kW (2.0 W/kg) on arrival at the abattoir. The total water vapour generation (Fig. 2) followed a similar pattern starting at 4.1 g/s (0.0006 g/s/kg), falling to 1.7 g/s (0.0003 g/s/kg), rising to 3.9 g/s (0.0006 g/s/kg) after the stop and finishing on 2.9 g/s (0.0004 g/s/kg).

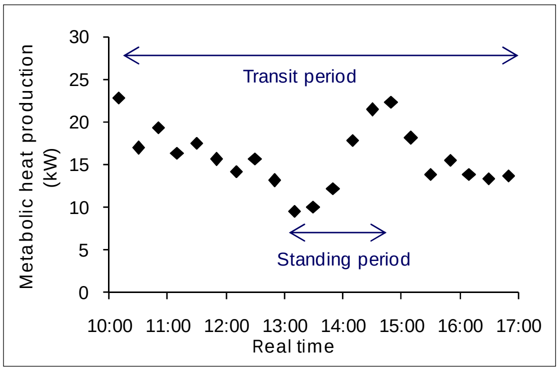

Figure 1
Variation in total metabolic heat production during interrupted transport
Group of 75 pigs (mean live weight 90 kg)

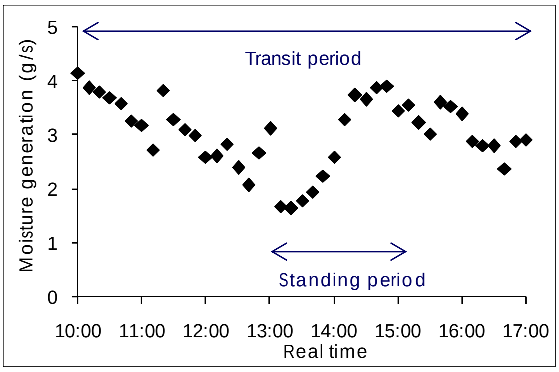

Figure 2
Variation in total moisture generation during interrupted transport
Group of 75 pigs (mean live weight 90 kg)

Sheep

The changes in metabolic heat production and moisture generation for two journeys are presented in Figures 3 and 4. The sheep journey required a mandatory stop to comply with driver's hours regulations in the United Kingdom. The total metabolic heat production during this journey (Fig. 3) rose to a maximum level post-loading of 7.4 kW (2.1 W/kg) which declined, with some intermediate minor peaks, to 3.6 kW (1.0 W/kg) before the stop. During the stationary period, heat production rose again to 5.5 kW (1.6 W/kg) and this level was maintained for the remainder of the transit period. The water generation (Fig. 4) had similar trends, with an initial peak of 1.2 g/s (0.0003 g/s/kg), 0.5 g/s (0.0001 g/s/kg) during the stationary period and a final value of around 1.2 g/s (0.0003 g/s/kg) on arrival at the abattoir.

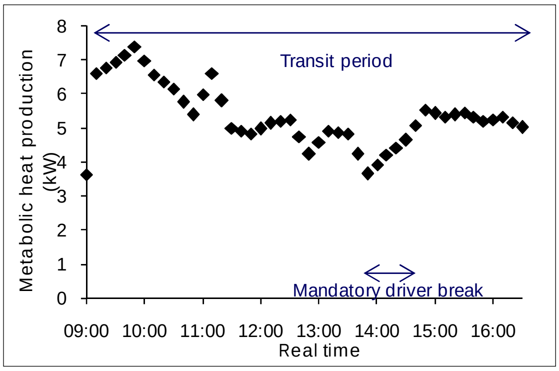

Figure 3
Variation in total metabolic heat production during transport
Group of 84 sheep in fleece (mean live weight 42 kg)

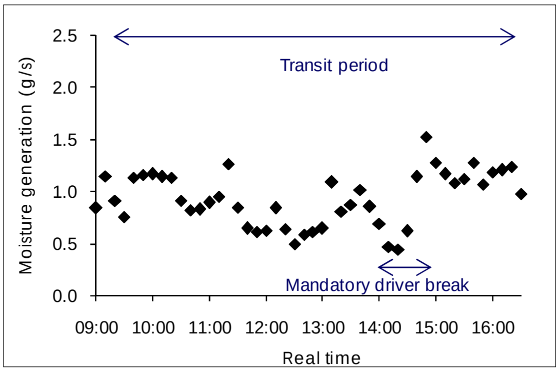

Figure 4
Variation in total moisture generation during transport
Group of 84 sheep in fleece (mean live weight 42 kg)

Evaluation of the experimental data

The experimental data have provided estimates of heat and moisture production by pigs and sheep in commercial transport conditions and thus provide the sound scientific basis for the determination of ventilation requirements. These data associated with knowledge of the target or optimal thermal conditions in transit for each species form the basis of the design of improved ventilation systems for livestock transporters.

It should be stressed that:

- both temperature and moisture production need to be considered when specifying acceptable thermal conditions during transport
- heat and moisture production can be variable and affected by the status and activity of the animals
- ventilation systems need to be designed to remove heat and moisture from the container to maintain acceptable thermal conditions for the animals.

The data derived from these studies have shown that the temperature *per se* contributes to the overall thermal load imposed on animals in transit and that moisture generated by the animals is also a significant contributory factor. The moisture measured within the ventilating air stream will include water not necessarily associated with recognised modes of heat loss (respiratory or transcutaneous evaporation). Some water will be derived from urine and faeces. However, the water will contribute to the micro-environment as latent heat within the transport container and it is this overall micro-environment that affects the animals. Partitioning the latent heat may prove impossible within the confines of a transport vehicle, but the overall effect can still be quantified. An important demonstration of this research is that it is not sufficient to specify ventilation regimes based solely on a consideration of dry bulb temperature. This has been quantified for poultry in transit (23, 24, 25, 26, 27) and ongoing studies will provide the equivalent information for red meat species (pigs, sheep and cattle) (M.A. Mitchell and P.J. Kettlewell, unpublished findings).

Determination of ventilation requirement – physical determination

Ventilation rates can be determined from purely physical considerations but the applicability of the findings requires due consideration of the physiological requirements of the animals. The basis of the physical determination is the specification of an acceptable temperature lift between air inlets and outlets, knowledge of the heat production of animals and the thermal properties of air.

The following equation can then be used to calculate the ventilation flow rate:

$VFR = TMHP / C_P \times \Delta T$

Where:

VFR = flow rate (m^3/s)

TMHP = total metabolic heat production (J/s) [Note: J/s is equivalent to W]

C_P = specific heat capacity of air (1 226 J/m^3/°C)

ΔT = acceptable rise in air temperature (°C)

For the case of pigs in transit, we can assume a total heat production of 1.5 W/kg, so on a deck containing 75 pigs each weighing 100 kg, the total heat metabolic production would be (75 × 100 × 1.5) = 11 250 W.

Thus, if we assume an acceptable temperature rise of 5°, then:

$VFR = 1\ 1250/(1\ 226 \times 5) = 1.84\ m^3/s$.

Clearly this determination is a first estimate of the potential requirement for ventilation and makes no allowance for heat losses through the structure of the vehicle. It is also derived from the total metabolic heat production and does not address the partitioning of heat loss between sensible and latent heat. It assumes that all the ventilating air passes over all the animals. However, application of this overall approach can define the ventilation requirements for each species for defined external climatic conditions, when thermal comfort zones are known and when the total heat and water vapour loads requiring dissipation are calculated from the number of animals on-board and their body weights. In this way, ventilation requirements and specifications can be obtained from the appropriate modelling procedures and applied to new engineering designs (37, 40).

Conclusions

This review has addressed the vital issue of thermal conditions during animal transport and the provision of engineering and design solutions that match on-board thermal micro-environments to the animals' biological requirements. The studies described are the first to quantify the heat and moisture generated by animals during road transportation under commercial conditions. Typically, pigs can be expected to generate approximately 1.5 W/kg of heat and produce 0.003 g/s/kg of water. Sheep, by comparison, generate 1.0 W/kg of heat and produce 0.001 g/s/kg of water. In both cases, these figures can be doubled following increased activity which may be encountered immediately after loading or during prolonged periods when the vehicle is stationary. Knowledge of the heat and moisture production of animals, together with the defined thermal comfort zones for each species, facilitates the design and development of practical mechanical or active ventilation systems which will improve both animal welfare and production efficiency. It is insufficient merely to consider the physics of the situation. Great emphasis is placed upon the definition of the physiological limits and thermal optima for the animals.

The practical implementation of these approaches to the design of mechanical ventilation systems for commercial livestock vehicles must take into account some additional features. Firstly, consideration must be given to having defined air inlets and outlets that ensure the ventilating air effectively reaches all animals in the container. Secondly, ventilation rates must maintain acceptable thermal conditions within the container throughout the entire transit period on both the moving and stationary vehicle. Finally, the practical embodiment of the improved ventilation systems must clearly be compatible with all the other requirements of commercial vehicles, including hygiene, ease of cleaning and the safety of both animals and humans.

The principles and approaches presented here are directly applicable to other species and other modes of transport. Specific situations will always require further investigation to ensure the appropriate physiological limits are defined and the engineering solutions are commercially viable. This fusion of the complementary disciplines of animal and veterinary science, engineering and physics will provide the sound scientific basis for future improvements in vehicle and container designs and transport practices which will underpin higher standards of animal welfare and more efficient animal production.

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