1-2006

Air Exchange Rate in a Horse Trailer During Road Transport

Joseph L. Purswell
Mississippi State University

Richard S. Gates
University of Kentucky, gates@bae.uky.edu

Laurie M. Lawrence
University of Kentucky, laurie.lawrence@uky.edu

Jamey D. Jacob
University of Kentucky

Timothy S. Stombaugh
University of Kentucky, tim.stombaugh@uky.edu

See next page for additional authors

AIR EXCHANGE RATE IN A HORSE TRAILER DURING ROAD TRANSPORT

J. L. Purswell, R. S. Gates, L. M. Lawrence, J. D. Jacob, T. S. Stombaugh, R. J. Coleman

ABSTRACT. *Horses traveling by road commonly experience heat stress conditions and poor air quality, which may be caused by insufficient ventilation; however, there are few estimates of air exchange in a horse trailer during transport. Air exchange rate was measured at ten locations within a four-horse trailer (internal volume 18.5 m^3) using tracer gas decay measurement to assess the adequacy of ventilation. Three vehicle speeds (13, 48, and 97 km h^{-1}) and three window configurations (all windows and roof vents closed, all windows open, all windows open and roof vents open forward) were tested with and without animals present in the trailer. External air temperature ranged from 22.3°C to 28.3°C with an average of 25.3°C, and internal air temperature ranged from 29.9°C to 34.8°C with an average of 31.3°C with animals present. Air exchange rate increased with vehicle speed and open window and vent area. The average air exchange rate over all vehicle speeds and ventilation configurations was 0.52 min^{-1} with animals present and 0.76 min^{-1} without animals. Without animals present, the maximum mean exchange rate was 1.42 min^{-1} at 97 km h^{-1} at the rear left window with all windows and vents open; the lowest mean exchange rate was 0.12 min^{-1} at 13 km h^{-1} with all windows and vents closed at the lower position of the rearmost stall divider. With animals present, the maximum air exchange rate observed was 0.84 min^{-1} with all windows and vents open and traveling at 97 km h^{-1}. Ventilation in the trailer was not adequate when compared to recommendations for stabled horses for any combination of vehicle speed or ventilation configuration. Increasing open vent area, either by increasing the number and size of roof vents or the size of windows in the sidewall, would be the most cost-effective means of increasing air exchange in a horse trailer.*

Keywords. *Animal transport, Tracer gas, Ventilation.*

Ventilation for horses during transport has been a concern since the late 19th century. Military records indicate that ventilation was of prime concern for maintaining the health of horses on board ships ferrying cavalry remounts (Hayes, 1902; Blenkinsop and Rainey, 1925). These same concerns still apply to modern road transport, as heat stress during transport and shipping fever remain problems. Typical modern livestock trailers are not equipped with mechanical ventilation systems and rely on vehicle movement to generate ventilation (Kettlewell et al., 2001). Horse trailers may be under-ventilated, as evidenced by increases in air temperature noted in previous studies (Smith et al., 1996; Green, 2004; Purswell, 2005).

Article was submitted for review in June 2005; approved for publication by the Structures & Environment Division of ASABE in November 2005.

The authors are **Joseph L. Purswell, ASABE Member Engineer,** Agricultural Engineer, USDA-ARS Poultry Research Unit, Mississippi State, Mississippi; **Richard S. Gates, ASABE Member Engineer,** Professor and Chair, Biosystems and Agricultural Engineering Department, **Laurie M. Lawrence,** Professor, Animal Sciences Department, **Jamey D. Jacob,** Associate Professor, Mechanical Engineering Department, **Timothy S. Stombaugh, ASABE Member Engineer,** Assistant Extension Professor, Biosystems and Agricultural Engineering Department, and **Robert J. Coleman,** Associate Extension Professor, Animal Sciences Department, University of Kentucky, Lexington, Kentucky. **Corresponding author:** Joseph L. Purswell, P.O. Box 5367, Mississippi State, MS 39762; phone: 662-320-7480; fax: 662-320-7589; e-mail: jpurswell@msa-msstate.ars.usda.gov.

Road transport can pose a significant threat to horse health and well-being. Heat stress conditions have been documented during transport (Stull, 1999; Stull and Rodiek, 2000; Green, 2004; Purswell, 2005). Dehydration occurred in horses that underwent 24 h of continuous transport in summer conditions with intermittent water and rest breaks (Smith et al., 1996; Stull and Rodiek, 2000), and long-distance transport has been shown to cause dehydration in slaughter horses (Friend et al., 1998; Stull, 1999; Friend, 2000). Poor air quality during transport has been reported, with increased concentrations of respirable particulates (Mansmann and Woodie, 1995; Smith et al., 1996; Oikawa et al., 1999), ammonia (Oikawa et al., 1995; Oikawa et al., 1999), and airborne microbes and fungi (Leadon et al., 1990; Smith et al., 1996; Oikawa et al, 1999). Transport has also been shown to cause increased incidence of respiratory infection (Oikawa et al., 1994; Oikawa et al., 1995; Racklyeft et al., 2000; Oikawa et al., 1999).

Wheeler (2003) recommended 340 to 595 m^3 h^{-1} per 450 kg horse during warm weather to limit temperature rise in stables based on heat balance calculations. Horses are most comfortable at air temperatures ranging from 5°C to 27°C (Sainsbury, 1987), and air temperatures exceeding 27°C can be considered warm weather. However, the thermal environment in a trailer is significantly different from that of a stable (Green, 2004), and it is likely that this recommendation is not adequate during transport. Ventilation must remove heat produced by the horses as well as the incident solar load and subsequent thermal radiation from the roof of the trailer, but as air temperature approaches body temperature, ventilation alone may not suffice. Purswell et al. (2003) measured air exchange rates in four locations of one horizontal plane in the headspace of an empty four-horse trailer with an internal volume of 18.5 m^3 during transport and found that the mean air exchange for this area of the trailer was one air exchange per minute. However, these measurements were taken with the upper rear door panel removed (but with similar vent and window configurations as the current study) and did not account for the formation of multiple zones within the air space.

The objectives of this experiment were: (1) to quantify air exchange rate at multiple locations within a horse trailer as a function of speed and open vent area, (2) to determine if air exchange varies with location in the trailer, and (3) to assess the effect of animal presence on air exchange rate.

Materials and Methods

Air exchange rate was measured using tracer gas concentration decay tests at ten locations within a horse trailer with and without animals present during summer weather conditions. Annualized extreme conditions (1%) for the Lexington, Kentucky, area are mean dry-bulb temperature of 31.6°C and mean coincident wet-bulb temperature of 23.3°C (ASHRAE, 2005a).

Three vehicle speeds were chosen (13, 48, and 97 km h^{-1}) to represent typical driving scenarios including city traffic (13 km h^{-1} or 8 mph), slower rural roads (48 km h^{-1} or 30 mph), and highway driving (97 km h^{-1} or 60 mph). Three ventilation configurations were tested: windows and vents closed, windows open and vents closed, and windows open and roof vents open forward. Opening and closing windows or roof vents is the only means to modify ventilation configuration, and all configurations (with the exception of opening the roof vents to the rear) were tested.

Data were taken on a highway near the University of Kentucky Woodford County Animal Research Center from 10:00 to 16:00 to avoid periods of heavy traffic. Four mature geldings, three Thoroughbreds and one Standardbred, ranging in mass from 520 to 570 kg, were used in this study. All horses were experienced travelers and had been previously transported in the trailer used in these experiments.

Trailer

A four-horse, slant-load, goose-neck trailer (Delta Manufacturing, Inc., Newport, Arkansas) was used, with overall dimensions of 2.13 m wide × 9.14 m long × 2.13 m high and a total floor area in the animal compartment of 8.67 m^2 (fig. 1). Total internal volume of the animal compartment is 18.5 m^3. Assuming the total body density of a horse is similar to that of water (1000 kg m^{-3}), the horses used in this experiment occupied approximately 2.2 m^3, resulting in an effective air volume of 16.4 m^3.

The four stalls are divided by moveable partitions hung on the left (driver's) side and measuring 1 m wide (at the head end) × 2.44 m long. Horses are oriented 62° from the centerline of the vehicle, facing the left (driver's) side of the vehicle. Stalls are numbered front to back (#1 through #4) to identify position in the trailer. Each stall has a window at the front and rear of each horse, as well as a roof vent above each head. Figures 2a and 2b show the layout of the trailer.

The driver-side windows measure 39.4 cm wide × 34.0 cm high, and the windows on the passenger (opposite) side measure 83.8 wide cm × 34.0 cm high. The windows slide open to expose 50% of their total area. The roof vents measure 25.4 cm × 10.16 cm and open either facing forward (as a scoop) or rearward with the cover at approximately a 45° angle. The roof vents were opened forward during this study. Total open window and vent area is approximately 1.05 m^2. The rear window above the loading ramp is 39.4 cm wide × 34.0 cm tall.

Tracer Gas Decay Measurements

Tracer measurements have been used to determine air exchange and infiltration in buildings (Dols and Persily, 1995; ASTM, 2000; ASHRAE, 2005b) and to quantify the performance of air conditioning systems in passenger vehicles (Conceicao et al., 1997; Kvisgaard and Pejtersen, 2003). The concentration decay method was selected for its relative insensitivity to tracer injection rate (ASHRAE, 2005b; Charlesworth, 1988; Sutcliffe, 1990) and because it is the only analysis appropriate for air spaces with multiple inlets and exhausts (ASTM, 2000).

Carbon dioxide (CO_2) was chosen as the tracer material because of safety concerns and availability of accurate and low-cost measurement equipment. While CO_2 generation by animals in the test area can introduce variability in the measurements, it would be extremely difficult to measure this generation accurately in real-time. The tracer decay method requires only relative changes in concentration to determine exchange rate, while more sophisticated techniques such as constant injection or constant concentration methods require accurate measurement of tracer injection (including generation in the space) and would not be suitable for this application (Charlesworth, 1988; Sutcliffe, 1990; ASTM, 2000).

Tracer gas was injected into the space until the concentration reached equilibrium at the upper end of the calibration range of the sensors. Fresh air entering the trailer diluted the concentration of the tracer gas, and an equilibrium concentration was achieved that depended on the exchange rate of fresh air. Shutting off the flow of a continuous tracer injection into a horse trailer was modeled as a step input forcing function, and since the mass balance relationship for tracer material is a first order, given the initial condition $C(t) = C_0$ when $t = 0$, the concentration of tracer material at any time is (Charlesworth, 1988):

$$C(t) = C_\infty + \frac{F}{Q} + \left(C_0 - C_\infty - \frac{F}{Q} \right) e^{-t/\tau} \qquad (1)$$

where

$C(t)$ = mass concentration of tracer
C_∞ = background concentration of tracer
F = generation rate of tracer material in control volume (m^3 s^{-1})
Q = volumetric flow rate of air through control volume (m^3 s^{-1})
C_0 = initial tracer concentration
t = time (s)
τ = ventilation time constant (s).

Note that for an empty trailer $F = 0$, and $C(t \to \infty) = C_\infty$. Mathematically, the value chosen for C_0 should not affect the resulting time constant if the data truly follow an exponential decay function. Values for C_0 were taken as the maximum concentration that occurred just after tracer injection ended.

Figure 1. Experimental horse trailer and truck.

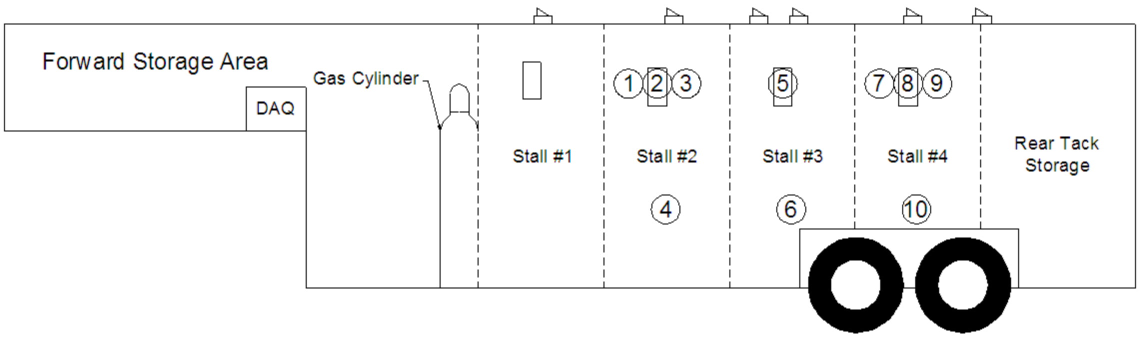

Figure 2a. Side view of trailer and measurement locations. Numbers indicate gas measurement locations; areas with multiple numbers indicate measurement locations in the same horizontal plane (DAQ = data acquisition equipment).

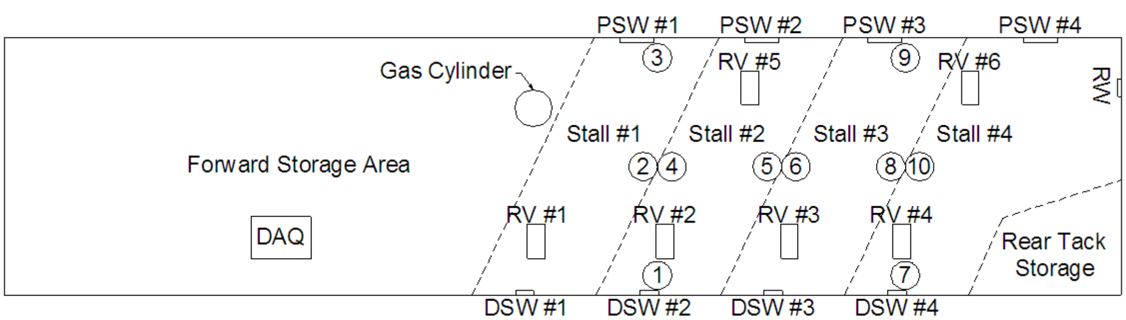

Figure 2b. Plan view of trailer and measurement locations. Dashed lines indicate internal walls or stall dividers (PSW = passenger side window, DSW = driver side window, RV = roof vent, and DAQ = data acquisition equipment).

The tracer mass balance relationship (eq. 1) can also be expressed in a non-dimensional form:

$$e^{-t/\tau} = \frac{C(t) - C_\infty - \frac{F}{Q}}{C_0 - C_\infty - \frac{F}{Q}} \qquad (2)$$

The volumetric flow rate (Q) is usually reported as volume per unit time or number of complete air exchanges per unit time. Air exchange rate was calculated from the following relationship (ASHRAE, 2005b; Charlesworth, 1988):

$$I = \frac{Q}{V} = \tau^{-1} \qquad (3)$$

where I is the air exchange rate (s^{-1}), and V is the volume being ventilated (m^3).

The ventilation time constant (τ) was found using a Marquardt-Levenberg non-linear regression algorithm in SigmaPlot (SPSS, Inc., Chicago, Ill.) by regressing the time-series CO_2 concentration data to equation 1. Values for C_0 and C_∞ were specified for each trial. The peak concentration reading at each location occurring after tracer injection was stopped was used for C_0, and the average free-stream CO_2 concentration measured over the duration of the test was used for C_∞. Values of τ were deemed acceptable if the associated standard errors (SE) were smaller than the published 63% response time for the CO_2 sensor (i.e., 30 s). Air exchange rate was then calculated from the time constant using equation 3.

Data Acquisition

Eleven infrared CO_2 sensors (Vaisala GMT 220, Helsinki, Finland) were used to measure CO_2 concentrations at various locations inside and outside the trailer. Of the eleven CO_2 sensors, six had an operating range of 0 to 10,000 ppm, and the remaining five units had a range of 0 to 5,000 ppm. The listed accuracy for sensors was 20 ppm ±2% of reading, and the response time (63% of full scale) for all CO_2 sensors was 30 s. Carbon dioxide probes were calibrated using a calibrator (GMK220, Vaisala, Helsinki, Finland) with N_2 as a reference gas and a calibration standard at 4513 ppm CO_2 (+N_2, analytical accuracy ±1%, Scott Specialty Gases, Plumsteadville, Pa.). Carbon dioxide concentrations were measured and recorded every 10 s; data were oversampled in order to more completely capture the dynamics of the response.

Six CO_2 sensor probes were mounted on the center of the upper and lower frames of the stall dividers, 107 cm from the sidewalls, denoted by the numbered circles in figures 2a and 2b. Sensor probes located on the top frame of the dividers were approximately 48 cm below the roof of the trailer; those located on the bottom were suspended approximately 63.5 cm above the floor. Four additional probes were mounted near driver side windows 2 and 4 and passenger side windows 1 and 3; these probes were affixed to the sidewall of the trailer approximately 48 cm below the roof and 14 cm away from the wall. The probes were positioned with the sensing element parallel to the floor, oriented towards the front of the vehicle. The external sensor was mounted at the forward portion of the roof of the trailer, as far as practically possible from the exhaust of the truck, to measure inlet air CO_2 concentrations. Signals from the CO_2 sensors were recorded using a data logger (CR23X, Campbell Scientific, Logan, Utah). A serial communications link between a notebook PC in the truck cab and the data logger in the trailer was used to monitor CO_2 concentrations within the trailer.

Carbon dioxide was injected using a diffuser made from a 3.18 cm OD × 3.35 m long piece of PVC pipe, mounted lengthwise in the center of the trailer at the ceiling (fig. 3). The diffuser consisted of five sets of three outlets spaced 50.8 cm apart, directing CO_2 laterally and downwards. The outlets were created by drilling 4.7 mm holes through the diffuser wall. The gas supply was located in the forward storage area of the trailer (fig. 2a). Gas flow was regulated using a pressure regulator (HPT500-40-580-DK, AirGas, Radnor, Pa.), and nylon gas supply lines were routed to the truck cab, so that the CO_2 supply could be controlled using a ball valve, and then to the rear of the trailer to the diffuser inlet.

External air temperature was measured using a combination air temperature/relative humidity sensor (S-THA-M002, Onset Computer Corp, Bourne, Mass.) and recorded with a HOBO Weather Station (H21, Onset Computer Corp, Bourne, Mass.). Internal air temperature was measured using Type-T thermocouples co-located with CO_2 probes and routed through a multiplexer (AM416, Campbell Scientific, Logan, Utah) and recorded with the CR-23X datalogger. Thermocouples were calibrated in a waterbath against an NIST traceable RTD thermometer with an accuracy of 0.05°C (DP95, Omega Engineering, Stamford, Conn.)

Measurement Procedure

Three replicates of exchange rate were obtained for each combination of the three vehicle speeds (13, 48, and 97 km h^{-1}) and the three window configurations. The measurements were performed both with and without horses. The following window configurations were used: all windows and vents closed, windows open and vents closed, and windows open and roof vents open forward. After the vehicle reached target speed, a short period of time (2 to 3 min) was allowed for flow patterns to develop; the tracer was continually injected during this time to promote mixing within the vehicle. Care was taken to avoid concentrations above the 5,000 ppm exposure limit recommended for humans (ASTM, 2000). When the tracer concentration reached the calibration level of the sensors, tracer injection was stopped; the sensor at location 4 was the first to reach maximum concentration, and its readings were used to control CO_2 injection. The concentration inside the trailer was allowed to decay to equilibrium while moving at a constant speed.

Figure 3. PVC diffuser for injection of tracer gas. Arrows indicate approximate locations of outlet holes.

Statistical Analysis and Experimental Design

Air exchange rates were analyzed as a randomized complete block arranged in a factorial structure with main effects of vehicle speed, vent configuration, location in the trailer, and stocking density. All statistical analyses used $\alpha = 0.05$ for limits of significance. Data were analyzed using an ANOVA with PROC MIXED in SAS (v8.0, SAS Institute, Cary, N.C.). Data were first analyzed for the empty trailer, and then a second dataset was formed from the combination of data from both data sets (with and without horses) at trailer speeds of 48 and 97 km h^{-1} to incorporate effects of animal presence.

Results

Examples of tracer concentration data are shown in figures 4 through 6. For purposes of comparison, non-dimensional concentration is used for the plots instead of actual concentration; non-dimensional concentration is defined as the right side of equation 2. As vehicle speed increased, both

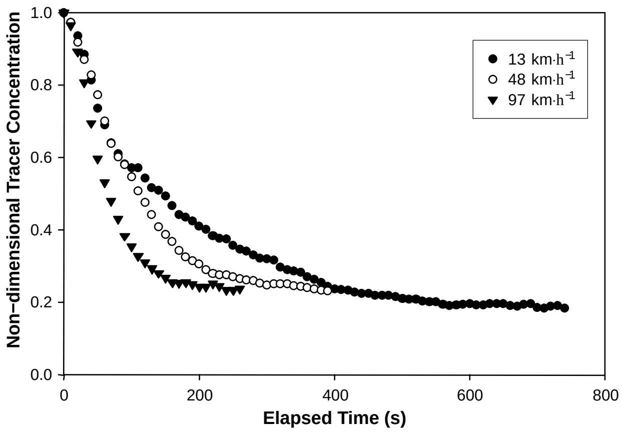

Figure 4. Non-dimensional tracer concentration (right side of eq. 2) at location 2 for the side windows open configuration. Initial slopes increase with increasing speed.

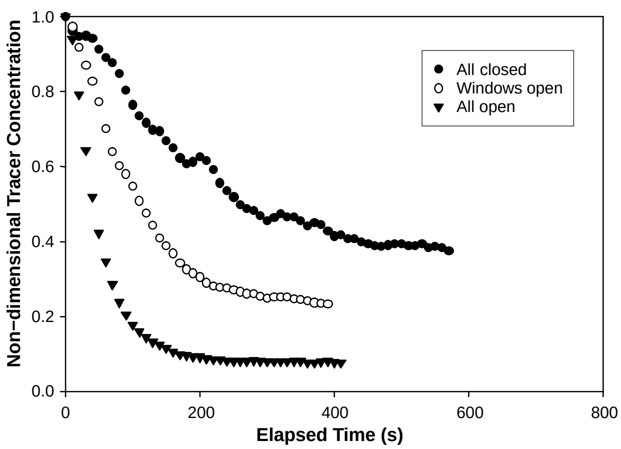

Figure 5. Non-dimensional tracer concentration (right side of eq. 2) at location 2 for 48 km h^{-1} with no animals present in trailer. Initial slopes increase with increasing open vent and window area.

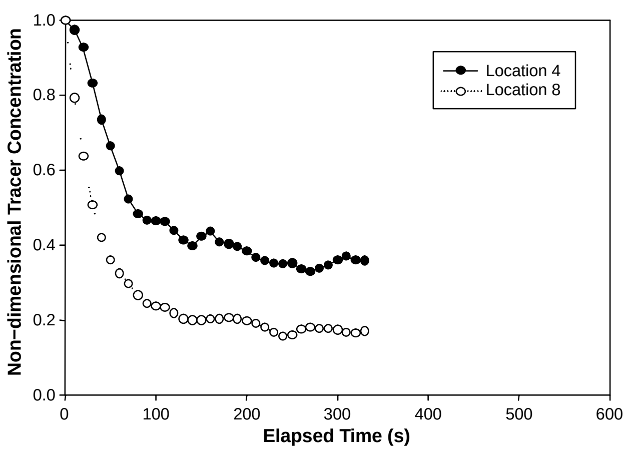

Figure 6. Non-dimensional tracer concentration (right side of eq. 2) at locations 4 and 8 for 97 km h^{-1} with animals present in the trailer.

the initial slope of the concentration plot and the time required to reach equilibrium were reduced (fig. 4). Similar behavior can be seen for increases in open vent area as well (fig. 5).

No valid data were collected for 13 km h^{-1} with horses in the trailer for any ventilation configuration; the additional

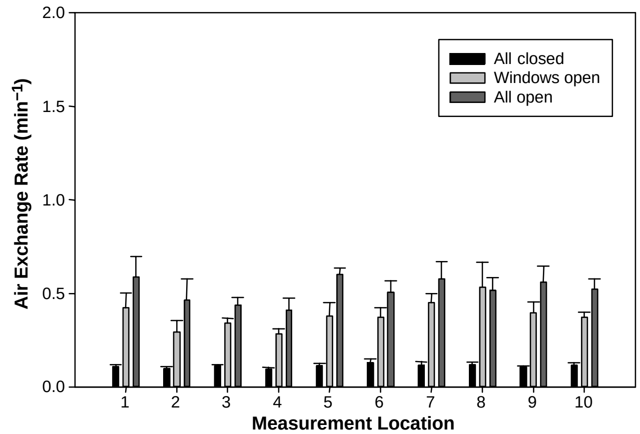

Figure 7. Mean air exchange rates for all measurement locations at 13 km h^{-1} with no animals present.

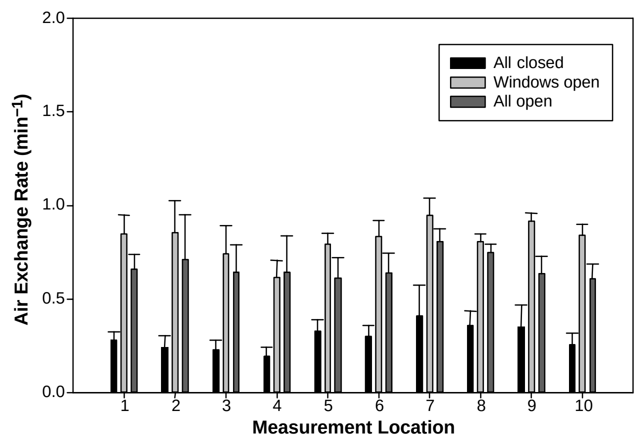

Figure 8. Mean air exchange rates for all measurement locations at 48 km h^{-1} with no animals present.

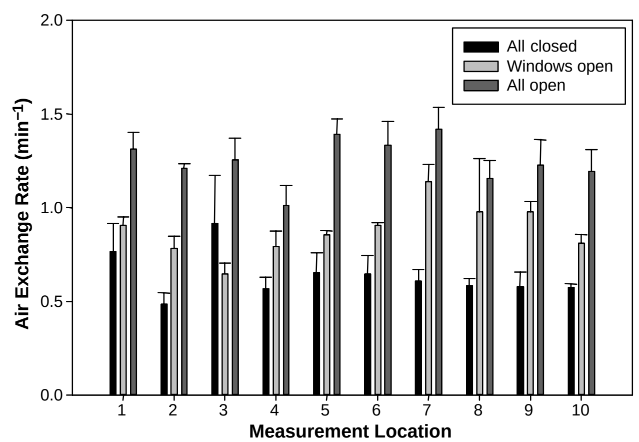

Figure 9. Mean air exchange rates for all measurement locations at 97 km h^{-1} with no animals present.

CO_2 produced by the horses coupled with low ventilation rates caused several sensors to saturate as the tracer concentration exceeded their calibration limits, indicating very low ventilation rates. Using a tracer other than CO_2 would eliminate this limitation; however, few gas detection systems can provide the sampling frequency necessary for accurate determination of concentration over the relatively short durations of these tests.

Example plots of exchange rate grouped by location within the trailer are shown in figures 7 through 11. The differences in exchange rate due to vent and window configuration are quite apparent in all plots, and comparison of plots of different speed show significant increases with increasing vehicle speed. The presence of animals increased the variability in mean air exchange, as evidenced by larger standard errors in comparison to those for the empty trailer shown in figures 9 and 10. For example, location 1 exhibited a large amount of variation due to its location near a window and very near the breathing zone of horses riding in that stall.

Air exchange rates generally increased with vehicle speed, and the closed configuration was consistently lower than the other two configurations. The average air exchange rate over all vehicle speeds and ventilation configurations was 0.52 min^{-1} with animals present and 0.76 min^{-1} without animals. The maximum mean exchange rate observed was 1.42 min^{-1} at 97 km h^{-1} at the rear left window with all windows and vents open; the lowest exchange rate observed was 0.12 min^{-1} at 13 km h^{-1} with all windows and vents closed at the lower position of the rearmost stall divider (location 10). Mean air exchange rates for all combinations of vehicle speed, ventilation configuration, and presence of animals are shown in table 1.

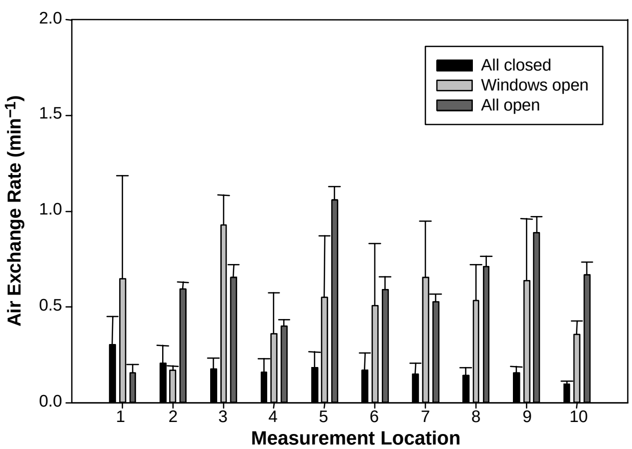

Figure 10. Mean air exchange rates for all measurement locations at 48 km h^{-1} with animals present.

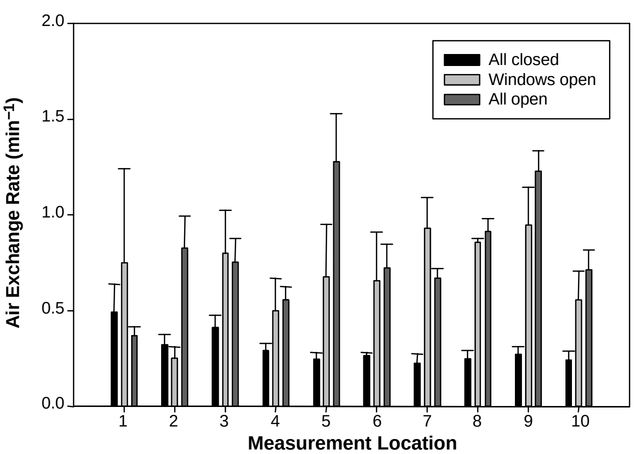

Figure 11. Mean air exchange rates for all measurement locations at 97 km h^{-1} with animals present.

The initial model used for statistical analysis of exchange rate in the empty trailer included vehicle speed, vent configuration, location, and interactions of all three effects with one another. From this analysis, vehicle speed ($P < 0.0001$), vent configuration ($P < 0.0001$), location ($P < 0.0001$), and the interactions of vehicle speed*vent configuration ($P < 0.0001$) and configuration*location ($P = 0.0272$) were found to be significant. The analysis was repeated omitting non-significant interactions (vehicle speed*location and vehicle speed*vent configuration*location), and means were analyzed for differences. As expected, tracer clearance rates increased with vehicle speed, and clearance rates for all three levels of vehicle speed were significantly different from one another ($P < 0.0001$ for all speeds). Tracer clearance rate also increased with open window and vent area, and clearance rates for all configurations were significantly different from one another ($P < 0.0001$). The configuration*location interaction term was significant because the location at the front passenger side window had similar air exchange rates for the windows open and all windows and vents closed configurations.

The same analysis procedure used for the empty trailer was used for analysis of data when animals were present, adding presence of animals to the initial model as a main effect. Since the 13 km h^{-1} trials with animals in the trailer yielded no useful data, comparisons of air exchange rates for presence of animals is limited to the 48 and 97 km h^{-1} cases. The analysis was repeated including only significant effects. Differences in exchange rate were calculated for vehicle speed, vent configuration, location, and presence of animals.

The results for vehicle speed were as expected. Exchange rates at 97 km h^{-1} were greater than those at 48 km h^{-1} ($P < 0.0001$). Exchange rates also varied with vent configuration, with all three configurations differing from one another ($P < 0.0001$ for all comparisons). The all windows and vents closed configuration yielded the lowest exchange rate, and all windows and vents open yielded the highest (table 2).

Table 1. Mean air exchange rates for each combination of vehicle speed, vent configuration, and animal presence over all central measurement locations (2, 4, 5, 6, 8, and 10). Vent configurations include: all roof vents and side windows closed, only side windows open, and all roof vents and side windows open.

Vehicle Speed (km h^{-1})	Ventilation Configuration	Animals Present	I[a] (min^{-1})		SE_I (min^{-1})
13	All closed	No	0.11	a	0.005
	Windows open	No	0.38	b,c	0.031
	All open	No	0.51	d,e	0.027
48	All closed	No	0.28	c	0.025
	Windows open	No	0.58	d,f	0.028
	All open	No	0.88	g	0.032
97	All closed	No	0.59	d,f	0.027
	Windows open	No	0.86	g	0.046
	All open	No	1.22	h	0.044
48	All closed	Yes	0.16	i,a	0.025
	Windows open	Yes	0.41	b,e	0.082
	All open	Yes	0.67	f	0.052
97	All closed	Yes	0.27	i,c	0.015
	Windows open	Yes	0.58	d,f	0.076
	All open	Yes	0.84	g	0.074

[a] I = air exchange rate; SE_I = standard error of I. Means followed by the same letter are not significantly different at $\alpha = 0.05$.

Table 2. Mean air exchange for all vent configurations over all combinations of vehicle speed, location, and presence of animals. Vent configurations include: all roof vents and windows closed, all windows open, and all roof vents and all windows open.

Vent Configuration	I (min^{-1})[a]		SE_I (min^{-1})
All open	0.82	a	0.027
Windows open	0.62	b	0.027
All closed	0.31	c	0.018

[a] I = air exchange rate; SE_I = standard error of I. Means followed by the same letter are not significantly different at $\alpha = 0.05$.

Air exchange rate was found to be significantly different among locations within the trailer (table 3). Location 4 tended to have significantly lower exchange rates than all other locations except for the upper center location (2) and lower rearmost location (10); however, mean exchange rates for locations 2 and 4 are numerically the lowest for all locations. This is supported by observations of animals transported in stall #1 routinely sweating more than those in the rearmost stalls during the conditions encountered. Heat stress conditions, defined as air temperature exceeding 30˚C (Cymbaluk and Christison, 1990), were observed during the experiments. Mean external air temperature ranged from 25.0˚C to 28.0˚C with an average of 26.1˚C, and mean internal air temperatures ranged from 29.9˚C to 34.8˚C with an average of 31.3˚C with animals present.

The presence of animals resulted in a 0.24 min^{-1} reduction of the overall mean exchange rate compared to that measured in the empty trailer (significant at $P < 0.0001$). Animal presence most affected exchange rate for the all windows and vents open and windows open configurations. The presence of animals also changed ventilation at window locations. With animals present, window locations had higher exchange rates for the windows open configuration versus the all windows and vents open configuration ($P < 0.0001$ to $P = 0.0014$).

Discussion

Unpublished data from researchers at the University of California − Davis (SCAHAW, 2002) showed increases in ventilation in a two-horse trailer when the upper rear door panels were removed, but no effort to quantify the results and provide estimates of air exchange were made. Only Purswell et al. (2003) has quantified air exchange in a horse trailer, using the same trailer as in this work but without animals and with the upper rear door panel removed. The current study was undertaken to expand on Purswell et al. (2003) and to characterize air exchange under realistic field conditions, e.g., with animals present in the trailer and with the upper rear door panel in place. The results presented here agree with Purswell et al. (2003) on increases in exchange rate with increasing vehicle speed; however, the previous study found no effect from window and vent configuration, with the difference presumably caused by the addition of the upper rear door panel in the current study. Location was found to have a significant effect on exchange rate in this study, whereas Purswell et al. (2003) found no effect of location, which was likely caused by the exclusion of locations outside of the headspace of the trailer and the absence of the upper rear door panel.

Table 3. Mean air exchange for each location in the trailer over all combinations of vehicle speed, vent configuration, and presence of animals.

Location	I (min^{-1})[a]		SE_I (min^{-1})
1	0.58	a,c,d	0.064
2	0.50	b,d	0.051
3	0.60	a,c	0.053
4	0.46	b	0.042
5	0.65	a	0.063
6	0.57	a,c,d	0.053
7	0.64	a	0.058
8	0.62	a,c	0.050
9	0.66	a	0.059
10	0.53	b,c,d	0.046

[a] I = air exchange rate; SE_I = standard error of I. Means followed by the same letter are not significantly different at $\alpha = 0.05$.

With animals present in the trailer and with all windows and roof vent open at 97 km h^{-1}, the average air exchange rate over three replicates was 0.84 min^{-1} at the six internal locations nearest to the animals. Based on the approximate effective trailer volume of 16.4 m^3, this translates to 827 m^3 h^{-1}, only half that recommended for a stable for the body weights of the animals used in this study. The reason for the difference in tracer clearance rate due to the presence of animals is not yet clear. The animals produce CO_2, and any sources of tracer within the space will affect concentration measurements and by extension the determination of clearance time constant. The horses also obstruct the airflow inside the trailer or increase resistance to airflow, reducing the amount of air moving through the trailer. Muirhead (1983) used flow obstructions in scale-model tests of ventilation in a cattle trailer and found reduced air velocities when compared to an empty model.

Currently manufactured trailer models are still very similar in design and configuration as the 20-year old trailer used in this study. Window placement, a window at each end of each stall, remains identical, but many current models use a larger 38.1 cm tall × 61.0 cm wide window. Uniform window sizes are common in modern trailers, and given the larger windows used on the passenger side in this trailer, total window area is only slightly larger in newer designs. Most current models provide one roof vent per stall, while the trailer used in this study has one per stall plus two additional vents. Total open window and vent area for the trailer used in this study was 1.06 m^2 (0.12 m^2 per m^2 animal occupied area), and window and vent area for a current model was estimated from manufacturer specifications as 1.15 m^2 (0.13 m^2 per m^2 animal occupied area), a difference of less than 10%. Given the similar aerodynamics of the trailers, as well as the similarities in windows and roof vents, results from this study should be applicable to current designs. Increasing open vent area, either by increasing the number and size of roof vents or the size of windows in the sidewall, would be the most cost-effective means of increasing air exchange in a horse trailer.

Conclusions

Road tests using tracer decay methods in a slant-load, four-horse trailer found air exchange rate to be affected by vehicle speed, vent configuration, and presence of animals. Exchange rate increased with vehicle speed and open window and vent area. For the empty trailer case, the "windows open" and "all open" configurations were similar, and there were no differences due to location. The data support the hypothesis that the trailer was under-ventilated at all speeds and ventilation configurations. The average air exchange rate over all vehicle speeds and ventilation configurations was 0.49 min^{-1} with animals present and 0.60 min^{-1} without animals, and ranged from a minimum of 0.12 min^{-1} at 13 km h^{-1} with all windows and vents closed to a maximum of 1.42 min^{-1} at 97 km h^{-1} with all windows and vents open.

Air exchange was found to be significantly different among locations. The forward locations (2 and 4) had lower clearance rates than the rest of the locations in the trailer, with the exception of the lower rear location (10). This is supported by observations of animals transported in stall #1 routinely sweating more than those in the rearmost stalls. Given the differences observed due to location in the trailer, the number of measurement locations within the trailer can be reduced and still provide representative measurements of clearance rate; measuring at locations 4 and 8 would provide estimates of minimum and maximum clearance rates in the trailer.

Mean air exchange rates were lower with animals present in the trailer, with reductions of 29% to 54% from those for the empty trailer. While the overall air exchange rate was reduced, the same trend of increasing with vehicle speed and open vent area were observed.

The measurement and analysis protocols presented here are capable of distinguishing differences between travel speeds, ventilation configurations, and presence of animals. Further investigation of the effects of animal presence is warranted; a series of tests might be conducted to determine which aspect of animal presence affects air exchange rate. A comparative study of trailers with various opening configurations would also be useful to determine what differences exist between designs.

Acknowledgements

The authors would like to acknowledge the assistance and support of Will Adams, Susan Hayes, Bryan Cassill, and Kristin Janicki in the execution of these experiments, and Professor Hongwei Xin for the loan of several CO_2 sensors. This study was funded in part by Multi-State Project W-173: Stress Factors of Farm Animals and Their Effects on Performance, and conducted under University of Kentucky Institutional Animal Care and Use Committee (IACUC) Protocol No. 00458A2002.

References

ASHRAE. 2005a. Chapter F28: Climactic design information. In *ASHRAE Handbook: Fundamentals.* Atlanta, Ga.: ASHRAE.

ASHRAE. 2005b. Chapter F27: Ventilation and infiltration. In *ASHRAE Handbook: Fundamentals.* Atlanta, Ga.: ASHRAE.

ASTM. 2000. E741-00: Standard test method for determining air change in a single zone by means of tracer gas dilution. West Conshohocken, Pa.: ASTM.

Blenkinsop, L. J., and J. W. Rainey. 1925. History of the Great War, based on official documents − Veterinary services. London, U.K.: HMSO.

Charlesworth, P. S. 1988. Air exchange rate and airtightness measurement techniques: An application guide. Coventry, U.K.: Air Infiltration and Ventilation Centre.

Conceicao, E. Z. E., M. C. G. Silva, and D. X. Viegas. 1997. Air quality inside the passenger compartment of a bus. *J. Expo. Anal. Environ. Epid.* 7(4): 521-534.

Cymbaluk, N. F., and G. I. Christison. 1990. Environmental effects on the thermoregulation and nutrition of horses. *Veterinary Clinics of North America − Equine* 6(2): 355-372.

Dols, W. S., and A. K. Persily. 1995. Study of ventilation measurement in an office building. In *Airflow Performance of Building Envelopes, Components, and Systems*, 23-46. ASTM STP 1255. Philadelphia, Pa.: ASTM.

Friend, T. H. 2000. Dehydration, stress, and water consumption of horses during long-distance commercial transport. *J. Animal Sci.* 78(10): 2568-2580.

Friend, T. H., M. Martin, D. Householder, and D. Bushong. 1998. Stress responses of horses during commercial truck transport. *J. American. Vet. Med. Assoc.* 212(6): 838-844.

Green, A. R. 2004. Physiological response of horses to transport. MS thesis. Lexington, Ky.: University of Kentucky, Department of Biosystems and Agricultural Engineering.

Hayes, M. H. 1902. *Horses on Board Ship: A Guide to Their Management.* London, U.K.: Hurst and Blackett.

Kettlewell, P. J., R. P. Hoxey, C. J. Hampson, N. R. Green, B. M. Veale, and M. A. Mitchell. 2001. Design and operation of a prototype mechanical ventilation system for livestock transport vehicles. *J. Agric. Eng. Res.* 79(4): 429-439.

Kvisgaard, B., and P. Pejtersen. 2003. *Measurement of Flow in Automobile Ventilation Systems.* Ballerup, Denmark: Innova AirTech Instruments. Available at: www.innova.dk. Accessed 10 May 2003.

Leadon, D. P., C. Frank, and A. Atcock. 1990. Recommendations to horse owners and their representatives on the transport of horses. Bern, Switzerland: FEI.

Mansmann, R. A., and B. Woodie. 1995. Equine transportation problems and some preventatives: A review. *J. Equine Vet. Sci.* 15(4): 141-144.

Muirhead, V. U. 1983. An investigation of the internal and external aerodynamics of cattle trucks. NASA Contractor Report 170400. Edwards, Cal.: NASA Ames Research Center.

Oikawa, M., M. Kamada, Y. Yoshikawa, and T. Yoshikawa. 1994. Pathology of equine pneumonia associated with transport and isolation of streptococcus-equi subs zooepidemicus. *J. Comparative Pathology* 111(2): 205-212.

Oikawa, M., S. Takagi, R. Anzai, H. Yoshikawa, and T. Yoshikawa. 1995. Pathology of equine respiratory disease occurring in association with transport. *J. Comparative Pathology* 113(1): 29-43.

Oikawa M., M. Kamada, R. Anzai, R. Kusunose, S. Hobo, H. Matsuda, H. Yoshikawa, and T. Yoshikawa. 1999. Effects of road transport on horses: Pathogenesis of transport-associated respiratory disease (shipping fever). In *Proc. 18th Annual Meeting of AESM*, 42-52. Reno, Nev.: Association for Equine Sports Medicine.

Purswell, J. L. 2005. Characterization of ventilation and thermal environment in a horse trailer during transport. PhD diss. Lexington, Ky.: University of Kentucky, Department of Biosystems and Agricultural Engineering.

Purswell, J. L., J. D. Davis, A. R. Green, R. S. Gates, L. M. Lawrence, and R. J. Coleman. 2003. Measuring ventilation in a horse trailer during transport. ASAE Paper No. 034091. St. Joseph, Mich.: ASAE.

Racklyeft, D. J., S. Raidal, and D. N. Love. 2000. Towards an understanding of equine pleuropneumonia: Factors relevant for control. *Australian Veterinary J.* 78 (5): 334-338.

Sainsbury, D. W. B. 1987. Housing the horse. In *Horse Management*, 69-91. J. Hickman, ed. New York, N.Y.: Academic Press.

SCAHAW. 2002. The welfare of animals during transport (details for horses, pigs, sheep, and cattle). Brussels, Belgium: European Commission, Health and Consumer Protection

Directorate-General, Scientific Committee on Animal Health and Animal Welfare.
Smith, B. L., J. H. Jones, W. J. Hornof, J. A. Miles, K. E. Longworth, and N. H. Willits. 1996. Effects of road transport on indices of stress in horses. *Equine Vet. J.* 28(6): 446-454.
Stull, C. L. 1999. Responses of horses to trailer design, duration, and floor area during commercial transportation to slaughter. *J. Animal Sci.* 77(11): 2925-2933.
Stull, C. L., and A. V. Rodiek 2000. Physiological responses of horses to 24 hours of transportation using a commercial van during summer conditions. *J. Animal Sci.* 78(6): 1458-1466.
Sutcliffe, H. 1990. A guide to air change efficiency. Coventry, U.K.: Air Infiltration and Ventilation Centre.
Wheeler, E. F. 2003. Horse stable ventilation. Cat. No. UB039. State College, Pa.: Pennsylvania State University, Agricultural and Biological Engineering Extension.