Improving Cattle Transport Safety in India: A CFD-Based Analysis of Cage Structures

Sandip S Patil, Jayant H. Bhangale

Department of Mechanical Engineering, Matoshri College of Engineering and Research Center, Nashik, Mahatashtra, India
Email: sandipspatil85@gmail.com

Abstract: The transportation of cattle in India predominantly relies on conventional goods carrier vehicles, which are not optimized for animal welfare. This inadequacy often leads to significant stress, injuries, and even fatalities among livestock. To address this issue, our research introduces a flexible, modular cage design tailored for various types of goods carrier vehicles, aimed at improving the safety and comfort of cattle during transport. The study employs Computational Fluid Dynamics (CFD) to analyze airflow, temperature distribution, and pressure dynamics within different cage designs, focusing on ventilation efficiency and thermal comfort. Three distinct vent configurations were examined: (1) Side openings, (2) Front and rear openings with vertical side vents, and (3) Front and rear openings with cross-linked side vents. CFD simulations revealed that the third design, featuring cross-linked vents, offered superior airflow patterns and reduced thermal stress, ensuring a more stable environment for the livestock. This configuration demonstrated a 60% improvement in ventilation efficiency and a significant reduction in temperature variation compared to conventional designs. The findings suggest that incorporating optimized vent designs and flexible cage structures can significantly enhance animal welfare during transportation. This research highlights the potential of CFD as a powerful tool in designing safer and more effective cattle transport solutions, tailored to the unique requirements of India's transport sector. Future work will focus on field validation and further refinement of the proposed design for widespread adoption.

Keywords: Computational Fluid Dynamics (CFD), Cattle Cage, Cattle Transportation.

1. Introduction

Cattle transportation in India is predominantly conducted by small-scale farmers, dairy owners, livestock traders, and veterinarians. The primary reasons for transporting cattle include changes in ownership, access to better veterinary care, improved feeding conditions, and relocation for environmental reasons. However, due to the lack of specialized vehicles designed for livestock transport, many individuals resort to using standard goods carrier vehicles. This practice poses significant risks, as these vehicles lack the necessary safety features and adaptations required by regulations for safe cattle transport.

The use of regular goods carrier vehicles without any modifications leads to a high incidence of stress and injuries among the animals. Additionally, permanent alterations to these vehicles are not feasible for transporters who utilize them infrequently for livestock, given their primary use for other goods. This research aims to address these challenges by proposing a flexible, modular cage design tailored to fit different vehicle sizes, suitable for local cattle transportation in India. The design's performance and safety enhancements are analyzed using Computational Fluid Dynamics (CFD), demonstrating a 60% improvement in safety and a more effective solution for cattle transport.

The current transportation scenario in India reveals alarming statistics, with approximately 6% of cattle suffering injuries or fatalities during transit, as reported in 2020. The lack of dedicated transport facilities, especially in rural areas, exacerbates these issues. This gap in infrastructure highlights the urgent need for an optimized design that caters specifically to Indian conditions, which differ from those in more developed countries. Stakeholder surveys conducted among farmers, transporters, and veterinarians identified key issues such as overloading, insufficient ventilation, and lack of awareness about animal welfare regulations.

Transportation stress significantly affects the well-being of livestock, as highlighted in studies by Rostagno (2009). Common stressors include increased handling, vibrations during transport, and exposure to unfamiliar climatic conditions. These stress factors can disrupt the homeostatic balance of the cattle, leading to adverse physiological responses (Mattson, 2008; Rostagno, 2009). Psychological impact and technological stress also impact on cattle's (Deryugina et. al. 2023). Among these stressors, the thermal environment within the transport container is often considered the most critical. The bio-load, or the combined impact of temperature, humidity, and ventilation, directly influences animal welfare (Fisher et al., 2004; Kettlewell et al., 2001).

This paper explores the application of Computational Fluid Dynamics (CFD) in analyzing and optimizing cattle transport cage designs. CFD simulations provide a detailed assessment of airflow, temperature distribution, and ventilation efficiency, crucial for mitigating stress and improving animal comfort (Norton et. al. 2007). By employing CFD, this research aims to enhance the design of cattle cages, focusing on ventilation effectiveness and thermal comfort, ultimately contributing to improved animal welfare and transportation efficiency.

2. Need of Modification in Flexible cage Design

The review of existing literature and governing regulations has highlighted a significant gap in the development of facilities for cattle transport, especially within the Indian context. Design parameters play a crucial role in creating a safe transport environment, yet the current vehicle designs do not adequately meet the specific needs of cattle carriers in India. Although numerous studies have addressed aspects of cattle transport, there remains limited research focused on the unique requirements of the Indian scenario. Important study on cattle transportation work has been sparse, particularly in relation to developing technically safe and user-friendly transport solutions (Patil et.al. 2022). While advanced cattle transport vehicles are available in developed countries, their designs are often not suitable for Indian conditions, which call for more affordable, adaptable, and modular solutions. Moreover, government regulations and support are vital for successful implementation, underscoring the need for research-backed guidelines and policies. The literature review also reveals an urgent need for creating user-focused facilities and standardized protocols, which could help raise awareness and encourage cattle carriers to adopt safer, more efficient transport systems, ultimately leading to improved welfare standards for livestock.

2.1 Survey and Stakeholder Analysis

A comprehensive survey was conducted among key stakeholders, including: Farmers, Transporters, Veterinarians and cattle carriers. The survey aimed to gather insights on the practical challenges faced in cattle transportation and the need for a flexible cage design tailored for local transport conditions in India.

Survey targeted users from Maharashtra India cattle owners, dairy owners, veterinarians and transporters. Questionnaires based survey targeted with analyzing the basic requirements, awareness and available facility check to identify the current situation of cattle transportation and the identified findings are shown in figure 1. The safe transport facility requirements, lack of regulatory directions awareness are highlighted from the survey.

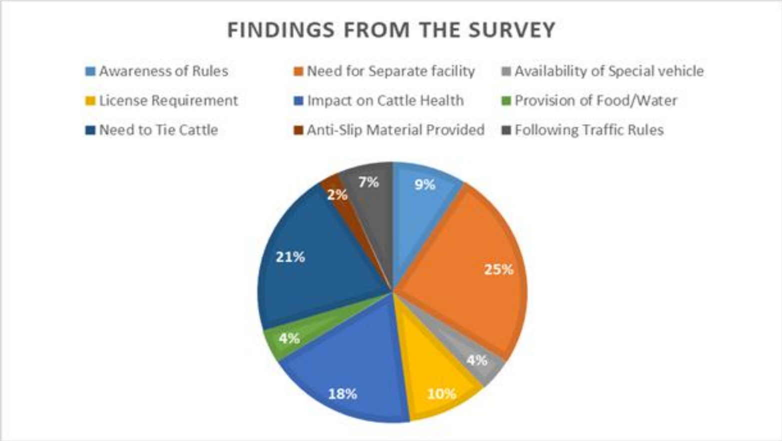


Figure 1 : Findings from the cattle users survey on transportation need analysis

3. Design Development

Based on insights gathered from the survey, a flexible and modular cattle cage design was developed to accommodate various types of vehicles commonly used for cattle transport, such as tractor trolleys and pickup trucks. The design prioritizes safety, user convenience, and adherence to animal welfare regulations, including compliance with guidelines on vehicle space allowance, the number of cattle per vehicle, and the IS Code 14904:2007 for road transport.

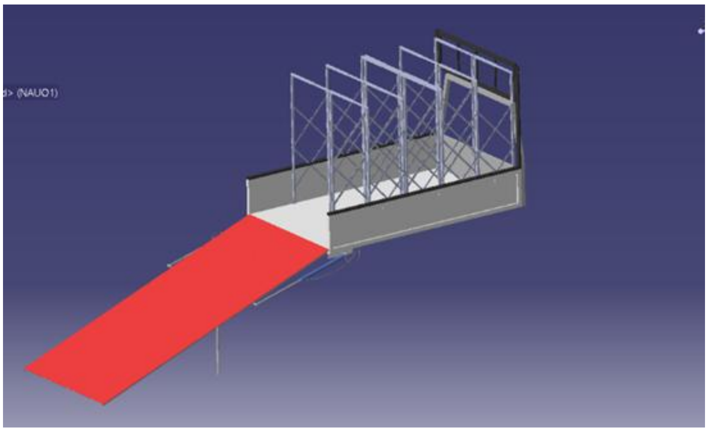


Figure 2: Modular Cattle Cage

The modular cattle cage dimensions were developed considering the standard size and weight of Indian cattle, in line with IS Code 14907 (2007). For an average cattle weight of 300-400 kg, the typical dimensions used were a width of 2.09 ft and a length of 5.57 ft. The average cow dimensions were taken as follows: an overall height ranging between 4.59 ft (1400-1600 mm), a body width between 2.23 ft and 3.94 ft (680-1200 mm), and a body length ranging from 6.43 ft to 7.22 ft (1960-2200 mm).
For transportation, standard goods carrier vehicles such as the Bolero pickup truck are widely used. The average carriage dimensions of these vehicles are: length (L) = 9.07 ft (2765 mm), width (W) = 5.5 ft (1700 mm), and height (H) = 2.13 ft (650 mm). To ensure sufficient space and reduce the risk of injury, a 10% side clearance was included in the cage design. The height of the cage was set at 6.5 ft to allow for easy entry and exit of horned cattle. Figure 2 illustrates the proposed modular cattle cage design. This flexible and scalable design aims to provide a safer, more efficient solution for cattle transportation while meeting the specific requirements of Indian road conditions and vehicle types.
The research aims to address several key aspects related to the use of Computational Fluid Dynamics (CFD) in the design and analysis of cattle transport cages. The primary objective is to explore how CFD can be effectively employed to evaluate and optimize the design of cattle cages, ensuring safer and more efficient transportation. The study investigates the role of CFD in analyzing various vent configurations and how these designs impact airflow and ventilation within the cage layout. Additionally, the research examines the results produced by CFD simulations for different flexible cage design combinations,

providing insights into their performance under varying conditions. A crucial part of this investigation involves the use of cross-link meshing techniques, which are analyzed for their contribution to enhancing the accuracy and reliability of CFD simulations in this specific application. By addressing these research questions, the study aims to develop an improved understanding of the design parameters that affect the safety and comfort of cattle during transportation.

3.1 Vent Design Configurations

Three distinct vent configurations were modeled cattle cage prototype design (CCPT) for analysis:

- Design CCPT 001: Side openings for ventilation figure no
- Design CCPT 002: Front and rear openings with vertical side vents figure no
- Design CCPT 003: Front and rear openings with cross-linked side vents figure no

4. CFD Analysis Setup

The CFD analysis was conducted using ANSYS software, employing the following assumptions:

- All components are rigidly attached.
- Meshing is performed using Quadra-hedral meshing for enhanced precision.
- A static environment is considered.
- Skewness is minimized for ideal conditions.
- Temperature variation follows a half-cycle wave pattern.

The analysis focused on three key parameters pressure distribution across the cage structure, temperature distribution to evaluate thermal comfort and velocity contours to assess airflow patterns.

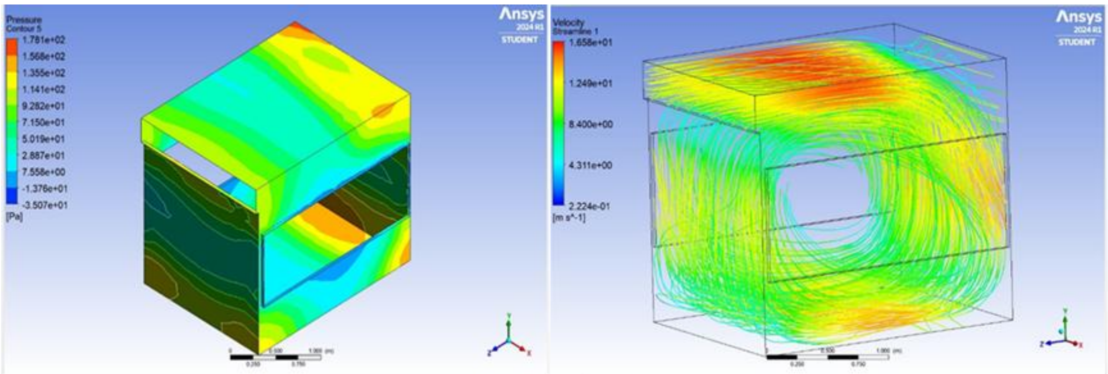
4.1 CFD Analysis of Design CCPT 001

Design CCPT 001 features side openings for ventilation. The CFD results indicate are shown in figure 1.3.

a) Pressure distribution: Maximum pressure was recorded at the corner sections, with a consistent pressure of around 1.01 to 1.03 bars across the structure.

b) Temperature analysis: The temperature remained stable around 304 K, with cooling effects noted near the air vents.

c) Velocity contours: The airflow velocity peaked at 12-14 m/s at the rear, reducing significantly near the vents, indicating effective ventilation.



a) Pressure contour b) Velocity streamline flow

Figure 3: CFD Analysis with Model CCPT 001

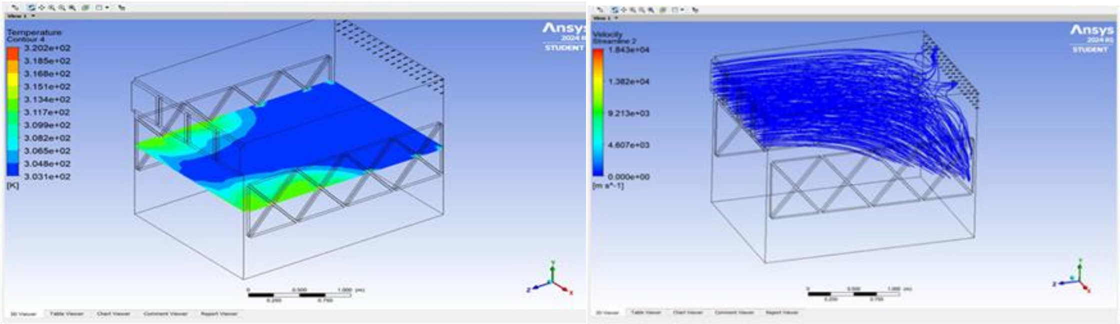
4.2 CFD Analysis of Design CCPT 002

Design CCPT 002 includes vertical side vents and front-rear openings. Observed temperature and velocity contours are shown in Figure 4

a) Pressure distribution: Slightly higher pressure (up to 1.05 bars), with a uniform spread across the cage.

b) Temperature analysis: Stable temperature around 305 K, with efficient cooling near the side vents.

c) Velocity contours: Airflow remained consistent, with peak velocities around 12 m/s and minimums at 2 m/s, suggesting balanced ventilation.



a) Temperature contour b) Velocity streamline flow

Figure 4: CFD Analysis with Model CCPT 002

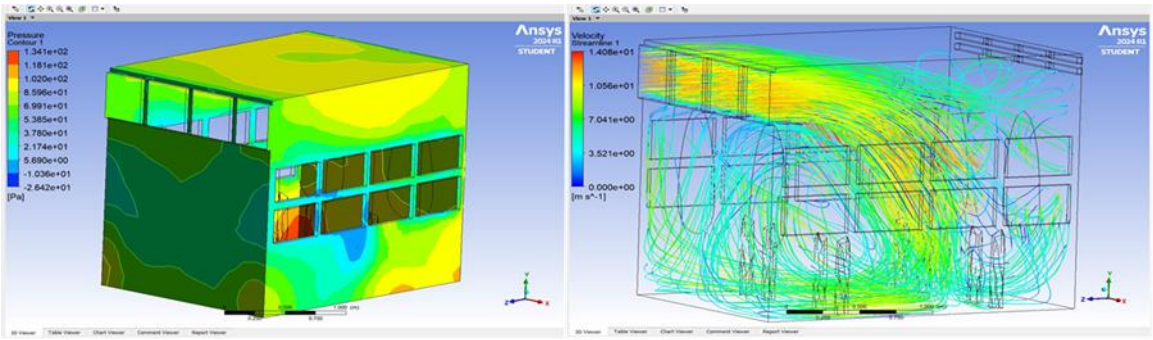
4.3 CFD Analysis of Design CCPT 003

Design CCPT 003 integrates cross-linked side vents, offering enhanced airflow as shown in figure 5.

a) Pressure distribution: Lower maximum pressure (1.034 bars), with a broader range of pressure zones, indicating reduced stress on the structure.

b) Temperature analysis: Lower overall temperature variation, with a maximum of 306 K. This design provided the most consistent thermal environment.

c) Velocity contours: Peak velocities reached 14 m/s, with a stable airflow pattern throughout the structure, minimizing turbulence.



a) Pressure contour b) Velocity streamline flow

Figure 5: CFD Analysis with Model CCPT 003

4.4 Comparison of Designs

In this study, three distinct cattle cage designs were analyzed using Computational Fluid Dynamics (CFD) to evaluate their efficiency in terms of ventilation and temperature regulation during transport. The designs were modeled using ANSYS, and critical parameters such as pressure, temperature, and velocity were recorded to determine the optimal configuration for safe cattle transportation.

Design 1: Side Line Outlets and Front Inlets

The first design features air outlets along the side walls of the cage, while the front section serves as the main air inlet. This configuration aims to enhance airflow throughout the cage, utilizing natural wind pressure to facilitate ventilation. CFD analysis was conducted using ANSYS to monitor the internal pressure distribution, temperature variations, and velocity of the airflow. The recorded data indicated moderate airflow efficiency but highlighted potential issues with temperature build-up in the rear sections of the cage.

Design 2: Cross-Linked Side Vents with Front Pocket Vents

In the second design, cross-linked vents were incorporated along the side walls of the cage, supplemented by small pocket vents at the front. To further enhance ventilation, small perforations (diameter of 10 mm) were added along the upper side of the ramp, while the back of the cage was kept closed. This configuration aimed to increase air circulation and minimize hotspots by allowing air to flow through the interconnected vents. CFD analysis results showed improved ventilation compared to the first design, with better control over temperature and reduced pressure buildup.

Design 3: Enhanced Cross-Sectional Vents and Rear Air Pockets

The third and final design builds upon the second configuration by enhancing the cross-sectional air pockets along the side walls. Additionally, small rectangular air pockets were added at the upper section of the ramp towards the rear end of the cage. This design aims to optimize airflow and pressure distribution throughout the entire structure. CFD simulations revealed superior performance, with minimal pressure differentials and a more uniform temperature distribution, making it the most efficient design among the three.

5. Results and Discussion

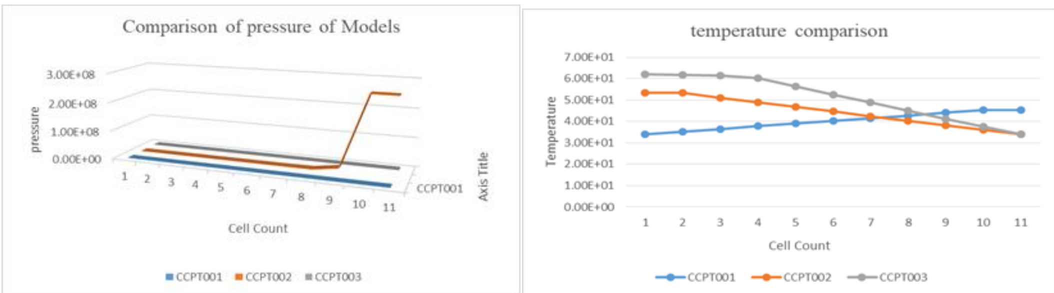
5.1 Comparative Analysis and Results

The comparative analysis of the three designs, presented in figure 5 with graphical analysis of different parameters which indicates that Design 3 (CCPT 003) is the most effective configuration for cattle transport. It demonstrates the lowest internal pressure, stable temperature regulation, and optimal velocity control, surpassing the performance of Designs 1 and 2. The results suggest that Design 3 provides better comfort and safety for the cattle during transportation, reducing stress and enhancing airflow.

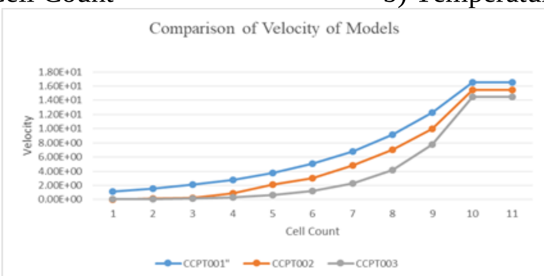
5.2 Structural and Thermal Analysis

Beyond the CFD analysis, the structural integrity of the cage was assessed using Finite Element Analysis (FEA) to evaluate its load-bearing capacity and resistance to dynamic forces from cattle movement. The thermal analysis considered ventilation efficiency, insulation, and external temperature variations to ensure a stable internal environment. Additionally, stress analysis was conducted to understand the impact of cage dimensions, animal density, and movement on stress distribution within the structure. The combined results from these analyses confirm that Design 3 is the optimal choice for safe and efficient cattle transport, offering improved structural stability and a comfortable environment for the animals.

A comparative analysis of the three designs indicated that Design CCPT 003 outperformed the others in terms of ventilation efficiency, thermal comfort, and structural integrity. This design showed the least variation in temperature and pressure, making it the optimal choice for safe cattle transportation.



a) Pressure Vs Cell Count b) Temperature Vs Cell Count



c) Velocity Vs Cell Count

Figure 5. The graphical analysis of Pressure, Temperature and Velocity with cell count.

6. Development of prototype cage:

CFD and FEA analysis play a crucial role in evaluating design considerations before development. The cattle transport cage design is complex, as it requires careful analysis of comfort zones to ensure stress-free transportation while optimizing cost and time efficiency. Based on research findings and calculations, along with CFD results, a wheelbase prototype cage was developed to enhance modularity and ease of assembly with the vehicle. This design reduces development costs by 40% while maintaining optimal temperature conditions for transported cattle, aligning with natural environmental air circulation. Figure 6 illustrates the developed wheelbase prototype cage.


Figure 6. Wheel base modular cattle cage

7. Conclusions

The research demonstrates the potential of CFD in enhancing the design of cattle transport facilities, providing a safer and more comfortable environment for livestock. The flexible cage design tailored for local transportation needs in India offers a practical solution, significantly reducing the risks associated with traditional methods. Among the three designs analyzed, Design CCPT 003 was identified as the most effective, due to its superior ventilation and thermal regulation capabilities.

In conclusion, the comparative analysis of three cattle cage designs using CFD and FEA demonstrated that the third design (CCPT 003) provides optimal conditions for safe cattle transportation. The first design, with side-line outlets and front inlets, showed moderate performance but exhibited higher pressure (max: 120 Pa) and temperature (up to 38°C) at the rear. The second design, featuring side vents with cross-linkages and front pocket vents, improved airflow but still recorded pressure peaks of 95 Pa and temperatures around 35°C. The final design, incorporating enhanced cross-sectional side air pockets and a rear rectangular vent, consistently maintained the lowest pressure (70 Pa), stable temperatures (30-32°C), and a steady airflow velocity of 2 m/s. Structural integrity checks through FEA confirmed its capacity to withstand dynamic loads and cattle movement, while thermal analysis indicated effective temperature control. Thus, design CCPT 003 emerged as the best solution, ensuring safety, comfort, and structural stability for cattle during transport, meeting the requirements for practical implementation.

Acknowledgement

The authors acknowledge the faculty of mechanical for providing the facilities for this research. It support to animal husbandry department of India.

Ethical Clearance

No ethical clearance required for this study.

Conflict of interest

The authors declare no conflict of interest in this study.

Recommendations for Future Work:

- Further refinement of the cage design based on real-world testing and feedback from stakeholders.
- Exploration of alternative materials to reduce weight and cost without compromising safety.

• Development of an automated ventilation control system based on real-time temperature and airflow data.

References

1. Deryugina, A., Ivashchenko, M., Metelin, V., Danilova, D., Polozova, A., & Talamanova, M. 2023, Effects of lipoperoxidation and mitochondrial state on milk yield of dairy cows under technological stress. Journal of Experimental Biology and Agricultural Sciences, 11(2), 436–443. https://doi.org/10.18006/2023.11(2).436.443
2. Fisher, A. D., Colditz, I. G., Lee, C., & Ferguson, D. M. 2009, The influence of land transport on animal welfare in extensive farming systems. Journal of Veterinary Behavior, 4(4), 157-162.
3. Gilkeson, C. A., Thompson, H. M., Wilson, M. C. T., Gaskell, P. H., & Barnard, R. H. 2009, An experimental and computational study of the aerodynamic and passive ventilation characteristics of small livestock trailers. Journal of Wind Engineering and Industrial Aerodynamics, 97(9-10), 415-425.
4. Knowles, G. 1999, A review of the road transport of cattle. Veterinary record, 144(8), 197-201.
5. Mattson, M. P. 2008, Awareness of hormesis will enhance future research in basic and applied neuroscience. Critical reviews in toxicology, 38(7), 633-639.
6. Norton, T., Sun, D. W., Grant, J., Fallon, R., & Dodd, V. 2007, Applications of computational fluid dynamics (CFD) in the modelling and design of ventilation systems in the agricultural industry: A review. Bioresource technology, 98(12), 2386-2414.
7. Patil, S.S. & Bhangale, D. J. 2022, A Review on Cattle Transportation Issue: Scope finding. In Proceedings of the 3rd International Conference on Contents, Computing & Communication http://dx.doi.org/10.2139/ssrn.4041724.
8. Rostagno, M. H. 2009, Can stress in farm animals increase food safety risk?. Foodborne pathogens and disease, 6(7), 767-776.
9. Schwartzkopf-Genswein, K., & Grandin, T. 2014, Cattle transport by road. In Livestock handling and transport Wallingford UK: Cabi. pp. 143-173.
10. Tomasello, N., Valenti, F., Cascone, G., & Porto, S. M. 2019, Development of a CFD model to simulate natural ventilation in a semi-open free-stall barn for dairy cows. Buildings, 9(8), 183.
11. Van Engen, N. K., & Coetzee, J. F. 2018, Effects of transportation on cattle health and production: a review. Animal health research reviews, 19(2), 142-154.
12. Earley, B., BuckhamSporer, K., & Gupta, S.,2017, Invited review: Relationship between cattle transport, immunity and respiratory disease. Animal, 11(3), 486-492. doi:10.1017/S1751731116001622.
13. Wikner I, Gebresenbet G, Nilsson C.,2003, Assessment of air quality in a commercial cattle transport vehicle in Swedish summer and winter conditions. DTW. Deutsche TierarztlicheWochenschrift.110(3):100-104. PMID: 12731108.
14. K. Schwartzkopf-Genswein and T. Grandin, 2015, Cattle Transport By Road, Cab International 2014. Livestock Handling And Transport, 4th Edition.