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Capturing CO_2 Emissions in the George C. Wallace Tunnel: A Case Study

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Abstract

This paper describes the design of a ventilation system to be paired with a carbon capture system. The ventilation system utilizes the geometry of the George C. Wallace tunnel, located in the City of Mobile, Alabama, USA to capture and redirect emissions to a direct air capture (DAC) device to sequester 25% of the total CO_2 mass generated from inside the tunnel. The total CO_2 mass rate for the westbound traffic between the week-day hours of 7 a.m. and 6 p.m. has been estimated between 2,300 to 3,000 lbs./hr. By sequestering these emissions, the overall surrounding air quality was shown to be improved to a level that mirrors that from the pre-US industrial era of 270 ppm.

Keywords

CO_2 Capture, Tunnel Ventilation, Air Flow Analysis, Jet Fan Sizing

1. Problem Background

The Clean Power Plan (CPP) establishes customized targets for states to reduce the carbon pollution produced by power plants that reflect each state's energy mix [1]. In February 2016, the US Supreme Court stayed the implementation of the CPP pending judicial review. Some states are choosing to continue to work to cut CO_2 emissions and explore new pathways to compliance. Alabama is one of those states that has chosen to continue working to cut CO_2 emissions, and currently ranks among the top ten states for potential CO_2 emission reduction in the United States [1]. The CPP has mandated Alabama to reduce its annual CO_2 emissions by 18.7 million short tons by 2030.

On July 1, 2021, the George C. Wallace tunnel, located in the City of Mobile, Alabama, USA, saw a range of 2,250 to 3,000 cars per hour traveling through the westbound tunnel between the hours of 7 a.m. - 6 p.m. This number of vehicles equates to a range between 2,300 to 3,000 lbs./hr. of CO2 emissions directly to the atmosphere. The goal of the study was to design a gathering system that utilizes the geometry of the Wallace tunnel to augment recapturing for at least 25% of the current CO_2 emissions and redirect to a DAC system to inhibit emissions from going to the atmosphere. By their very nature, tunnels are susceptible to higher concentrations of CO_2 as compared to other open-air locations. This project took advantage of that geometry by utilizing a collection system to channel the CO_2-laden air directly to a DAC system while also allowing for minimal size requirements as compared to other open-air systems thus allowing for greater efficiency.

The main objective of the gathering system is to utilize a series of fans along the tunnel to collect CO_2 particles from the elevated concentration in the tunnel air and flow these particles into a DAC unit. For the scope of the project, this system has been sized to accommodate 600 to 760 lbs./hr. Assuming the current CO_2 levels in the tunnel, this correlates to an air rate range of 60,500 to 62,300 cubic feet per minute. The Wallace tunnel is approximately 3,000 ft long, and three jet fans are to be strategically located to maximize the potential harvesting capability of the CO_2. Each designed jet fan is sized for a minimum of 25,000 cubic feet per minute, and they have been individually ducted to a common header for discharge into the DAC system.

For computational purposes, the authors assumed the gathering system would be used to feed an Adsorption style unit much like the unit that is currently in development with Climeworks [2]. The Adsorption unit uses solid materials such as zeolites or activated charcoal as a metal-organic framework to trap the CO_2 molecules as the air passes through.

1.1. Ventilation and Carbon Capture Technologies for Tunnels

Ventilation systems are critical for maintaining air quality and safety in tunnels, particularly in road and rail tunnels where vehicle emissions can accumulate. The primary objectives of tunnel ventilation systems are to remove pollutants such as carbon monoxide (CO), nitrogen dioxide (NO_2), and particulate matter, to control smoke in the event of a fire, and to provide fresh air for passengers travelling through the tunnel. Generally speaking, there are three major types of ventilation systems employed within tunnels: (1) Longitudinal Ventilation which uses jet fans to create airflow along the tunnel length, pushing or pulling air through the tunnel, (2) Transverse Ventilation which supplies and exhausts air through ducts running parallel to the tunnel, ensuring even distribution of fresh air, (3) Semi-transverse Ventilation, which is a combination of longitudinal and transverse systems, supplying fresh air at intervals along the tunnel, and (3) Natural Ventilation, which utilizes the tunnel's geometry and natural airflow, typically used in shorter or less trafficked tunnels. Extensive studies have been conducted on optimizing fan placement and operation within tunnels, as well as on how to improve current tunnel ventilation systems to better control car emissions, contaminants, and excessive temperatures [3] [4].

As carbon capture technologies are coupled with ventilations systems within metropolitan tunnels, these technologies can efficiently manage and reduce the environmental impact of vehicular traffic. Integrating ventilation and carbon capture systems in tunnels can enhance air quality by removing both traditional pollutants and CO_2 emissions. Research has been focused on improving the efficiency of CO_2 capture and reducing the cost of these technologies to make them more viable for widespread use. Studies have also been conducted to explore the potential of integrating carbon capture with renewable energy sources to offset the energy requirements of the capture process [5]-[11].

1.2. Design Requirements

Based on a reported pollutant concentration measurement study from 2020, max concentrations of pollutants have been found to occur in the latter half of a tunnel structure [12]. For this reason, the location of the gathering system must be near the tunnel exit to maximize gathering capability for the sake of cost. Three tunnel jet fans are to be located along the second half of the tunnel. The first one will be located at the midpoint approximately 1,500 ft from the exit, the second unit located close to 750 ft from the tunnel exit, and the last one within 100 ft of the exit. The duct gathering system will be constructed using common corrugated galvanized mild steel ducting. The discharge duct extends from the tunnel jet to the main gathering header. If necessary, a pretreatment system will be used upstream of the DAC unit to knock out the volatile organic compounds (VOCs) to prevent unnecessary buildup at the DAC contactor. Contactor housing dimensions have been assumed to be 40ft × 16ft × 8.5ft. This system can also provide an added level of safety to remove smoke in case of a fire and allow additional evacuation time for bystanders. This is represented in the isometric view in **Figure 1** and the longitudinal view in **Figure 2**.

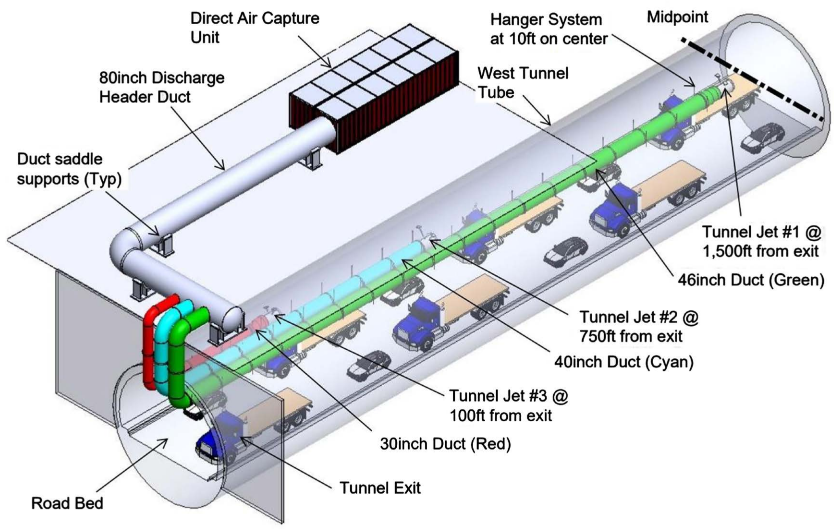


Figure 1. Conceptual isometric view.

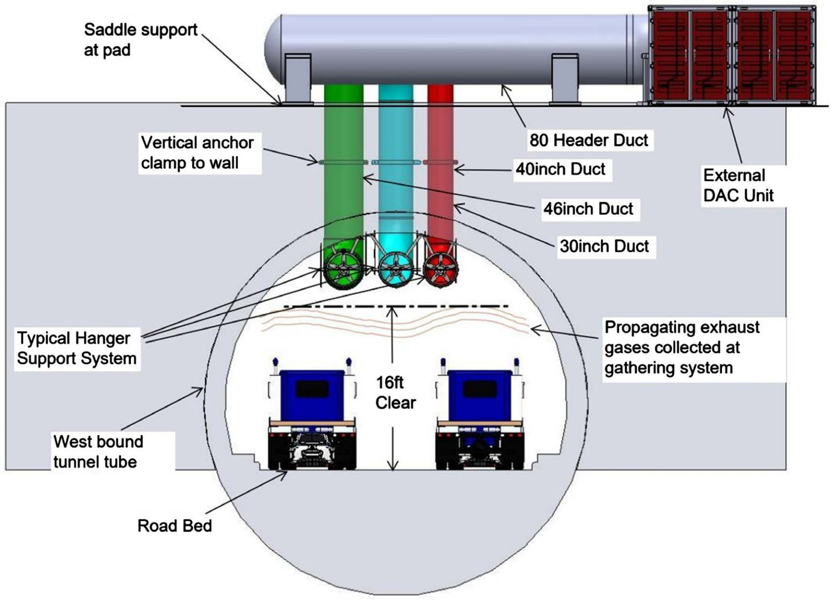


Figure 2. West bound elevation.

Defined functional requirements for the study are noted in Table 1.

The authors also identified and abided to the applicable federal, state, and local codes that had to be met for the project. These are shown in Table 2.

Table 1. Project functional requirements.

Requirement #1	Ability to move air from inside the tunnel to a DAC system outside of the tunnel	*Tunnel jets have been strategically located to maximize gathering capacity*
Requirement #2	Collect at least a 25% total current CO2 mass rate	*This defines the minimum amount of air required for equipment sizing*
Requirement #3	System must be secured to tunnel ceiling to prevent road obstructions	*Clearance and safety requirements as per the current highway safety guidelines*
Requirement #4	System also gathers entrained smoke and VOC particles	*Capable of withstanding concentrations of smoke and VOCs*

Table 2. Project applicable codes.

National Cooperative Highway Research Program (NCHRP) Guidelines for Emergency Ventilation Smoke Control in Roadway Tunnels
National Cooperative Highway Research Program (NCHRP) Synthesis 415 Design Fires in Road Tunnels
National Fire Protection Association (NFPA) 502
US Department of Transportation Federal Highway Administration Publication FHWA-NHI-10-034 Dec 2009
American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Heating Ventilation and Air Conditioning (HVAC) Applications
National Highway Institute (NHI) Smoke Control in Roadway Tunnels
National Cooperative Highway Research Program (NCHRP) Report 525
Alabama Building Code 2021—Chapter 16 (Structural Design) and Chapter 22 (Steel)
Mobile, Al Building Code 2023—Chapter 11 (Industrial Structures within City Limits)

2. Project Methodology

As previously stated, CO_2 levels in the tunnel were estimated to be between 2,300 and 3,000 lbs./hr. on July 1, 2021 (see **Figure 3**). The tunnel currently utilizes a ventilation system that can provide up to a rate of 700,000 cubic feet per minute (CFM) into the air space, creating a positive pressure atmosphere occupied by the regular traffic where the air space is then vented to the atmosphere at the open ends at the entrance and exits. As a result, the existing system cannot capture any of the pollutants emitted inside the tunnel. Based on the provided data from the Alabama Department of Transportation [13], redirecting at least 25% of the CO_2 mass rate required the project scope to accommodate 600 to 760 lbs./hr. Assuming the highest daily concentration levels between the hours of 7 a.m. to 6 p.m., the required airflow rate is between 62,500 to 62,300 CFM. The change in the required air rate is demonstrated in **Figure 4**. Also, it should be noted that a negative pressure system could be utilized to aid in the abatement of smoke and Volatile Organic Compounds (VOC).

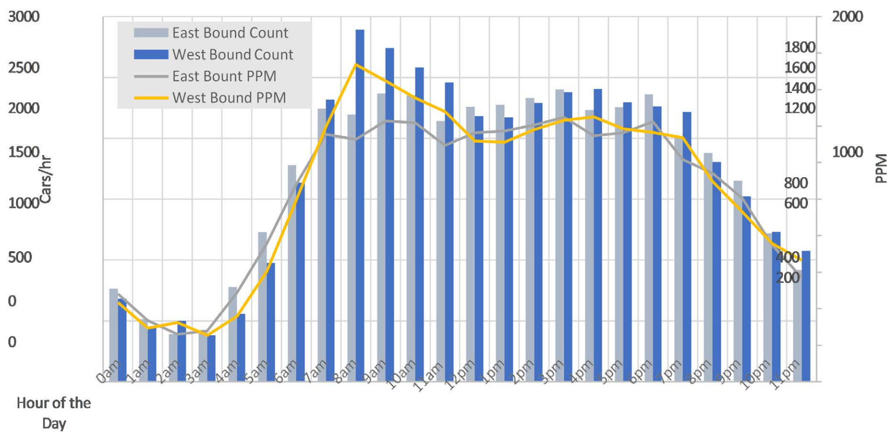


Figure 3. July 1st, 2021, Traffic Vs CO_2 levels.

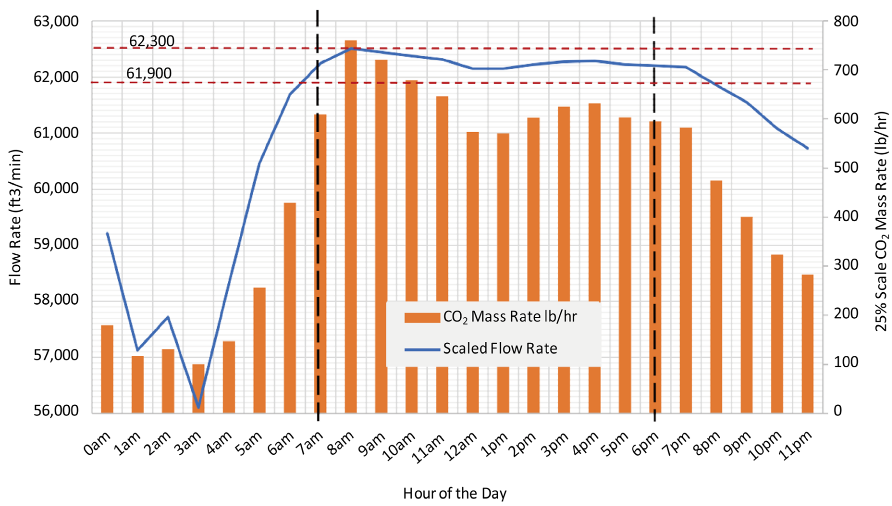


Figure 4. Emissions flow curve.

2.1. Material Selection

2.1.1. Jet Fan Sizing

Based on the calculated total required air flow rate of 60,300 CFM in the design basis, the authors assumed that tunnel air could be collected and transmitted to the DAC system effectively using three independent zones each at 20,767 CFM along the identified peak potential area in the ladder half of the tunnel. The jet fan sizing was then chosen based on the next available size that was larger than the calculated zone rate. For this purpose, the authors opted to utilize three Novenco AZN 900/350-6 A53 units with an available discharge rate of 25,000 CFM each at 2.83 inWC for a combined total rate of 75,000 CFM. Duct sizing was evaluated for each separate run to allow a minimum of 1 inWC at the main header located at the end of the tunnel up to the suction of the booster fans. Each jet fan unit utilizes approximately 13 hp for a combined total of 39 hp for the entire gathering system.

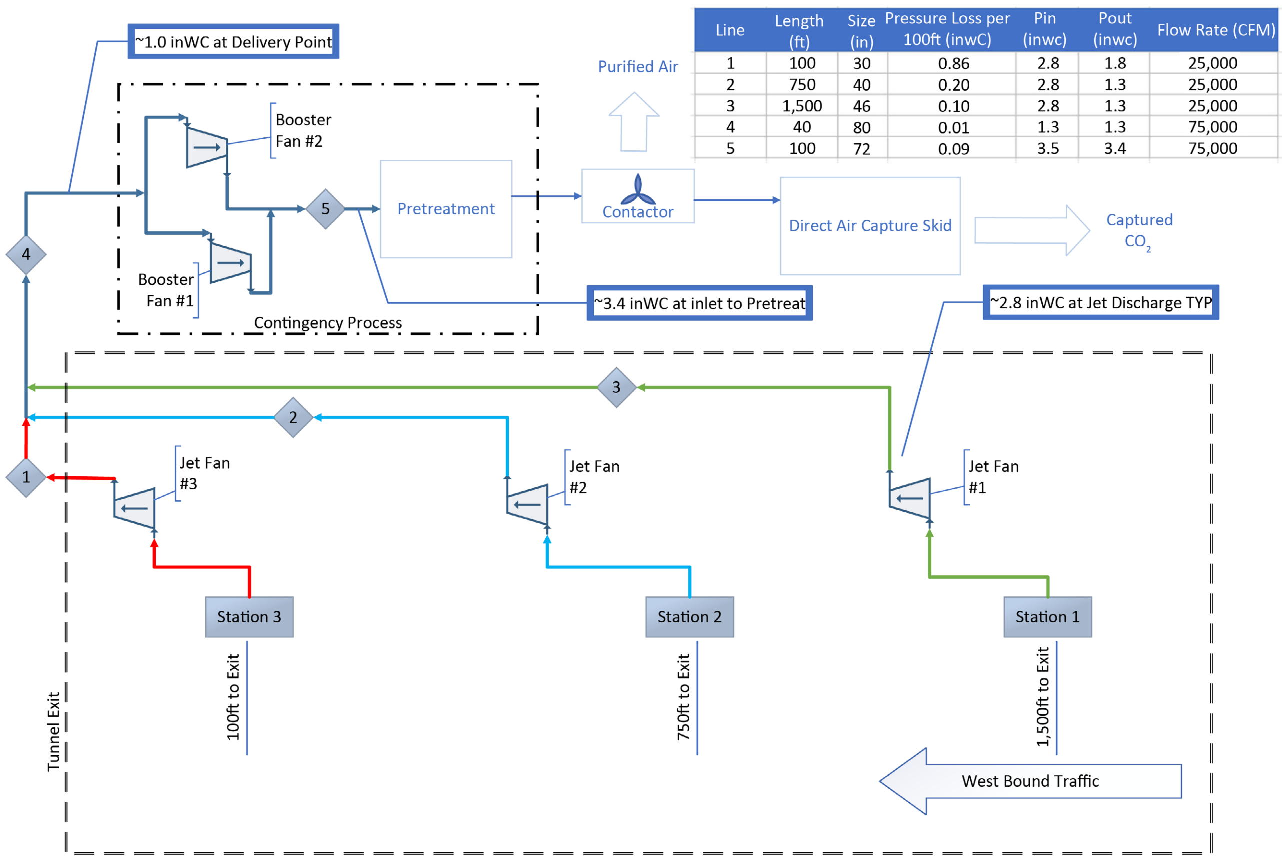
Since the tunnel air contains a greater concentration of VOC as compared to the open-air source that the DAC was originally designed, there could be additional buildup of soot and hydrocarbons that could develop and render the DAC ineffective. For that purpose, the authors of the study considered a contingency option where an additional set of fans is used downstream of the gathering system as a separate stage to boost the airflow pressure and allow for additional losses for utilization with a pretreatment system. This pretreatment would consist of a wide spot in the feed to the DAC contactor where the flow velocity is reduced to allow for heavier entrained particulate to fall out of the stream. For this purpose, two ZerAx AZN 1000/350-6 A55 units were chosen and placed in a parallel configuration. This modification increases the overall discharge pressure of the system by an additional 3.4 inWC before entering a pretreatment system. Since each booster fan is approximately 25 hp, the overall power requirements increased by an additional 50 hp. Although this modification more than doubles the power requirement from the original design, it does however limit the issue of increasing original duct sizing any further. The overall process has been reflected in **Figure 5** on the process flow diagram.

2.1.2. Duct Sizing

The duct sizing requirements for each run were evaluated for use with the selected fan at the respective lengths of 100 ft, 750 ft, and 1,500 ft based on the three preestablished zones. The required duct diameters were based on a minimum supply pressure of 1 inWC at the contactor assuming the 25,000 CFM rate. A thirty-inch, forty-inch, and forty six-inch ducts were selected, respectively.

2.1.3. Duct Support System

For the material selection for the support system, the decision was made to go with a simple but durable approach. An ASTM A193 Grade B7 material was utilized for the bolting and anchor system. This material has a high yield strength and ultimate tensile stress, making it a reliable option for demanding structural



Line	Length (ft)	Size (in)	Pressure Loss per 100ft (inwC)	Pin (inwc)	Pout (inwc)	Flow Rate (CFM)
1	100	30	0.86	2.8	1.8	25,000
2	750	40	0.20	2.8	1.3	25,000
3	1,500	46	0.10	2.8	1.3	25,000
4	40	80	0.01	1.3	1.3	75,000
5	100	72	0.09	3.5	3.4	75,000

Figure 5. Process flow diagram.

applications. Its durability and simplicity align well with the project requirements. A 5/8” ASTM A193 Grade B7 material was used for the anchor bolt assembly. The embedment depth was based on the manufacturer’s minimum embedment depth chart, which is 2-1/2” for a 5/8” undercut anchor. Each anchor would require 3,323 lbs. for pull out. It was be noted that deeper embedment will yield higher tension and shear capacity. Adhering to the manufacturer's guidelines ensures the anchor’s reliability and performance.

These values were based on 2,500 psi concrete. Normal substantial pressure ranges from 3,500 to 5,000 psi. The final duct hanger design is shown in Figure 6.

2.2. Study Analyses

2.2.1. Jet Fan Support Rod FEA

The conducted Finite Element Analysis (FEA) in this study employed a 735 lbf external force for the All-thread, calculated from the fan’s total weight divided by 4. In Figure 7, the highest yield strength observed stands at 3,725 psi. Notably, the material yield strength for ASTM A193-Gr B7 is 105,000 psi. The safety factor for this material far exceeds 100. This demonstrates that the material selected for the supporting application is adequate for use.

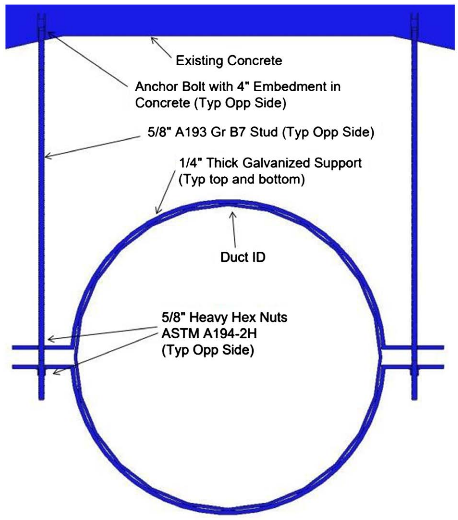


Figure 6. Duct hanger detail.

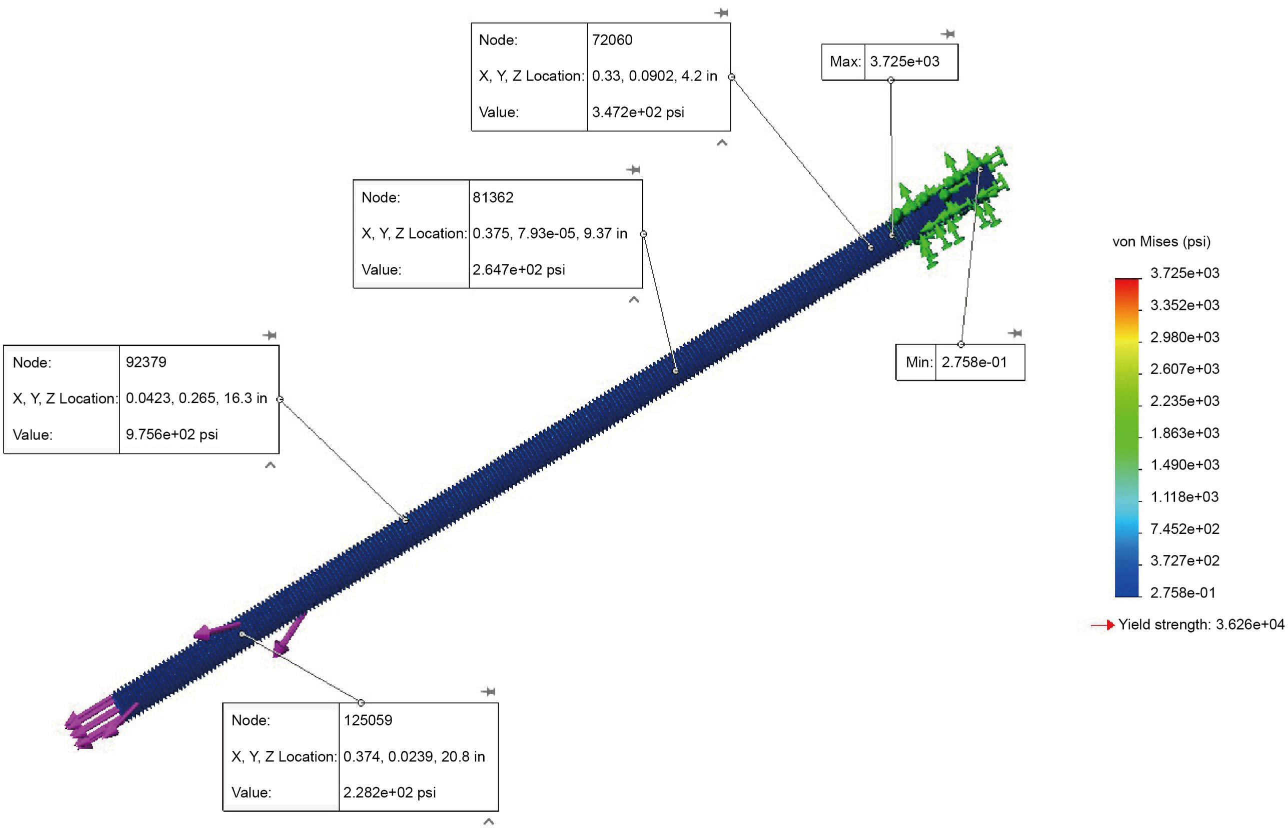


Figure 7. Jet fan all-thread support rod FEA analysis.

2.2.2. Jet Fan Thrust Forces

For the potential forces that could be acting on the tunnel due to the thrust developed by the fans, the thrust forces were evaluated. Through careful consultation with the Tunnel Jet Fan manufacturer, Novenco, it was decided that the AZN 900/350-6 model aligns impeccably with the specific demands of this project. The decision to horizontally mount the fans onto the tunnel's ceiling was strategic, ensuring optimal performance. Operating at a substantial volume flow rate of 25,000 CFM, the fan's design incorporates a flexible duct connection on the outlet alongside duct spigots and anti-vibration dampers; thus, reinforcing its adaptability and functionality. Moreover, the fan's capability to effectively manage fire smoke, CO_2, and nitrogen dioxide ventilation underscores its suitability and robustness for project objectives. Furthermore, the fans' sound emission, as per specifications, is less than the recorded 100.5 decibels inside the George Wallace tunnel. This underscores the project's commitment to not creating additional hazards in the surrounding area.

2.2.3. Dynamic Flow Analysis

For potential flow, the authors utilized PyroSim to conduct a qualitative analysis. PyroSim is typically used to simulate smoke patterns to assess ventilation designs for fires in buildings.

Since the smoke particulate and CO_2 are somewhat similar, it was assumed that the model would provide an accurate representation of the intended design. A rudimentary model was generated to assess the quality of the flow to the inlet of one fan. The model cross-section is approximately 23 feet tall to mimic the available overall height of the distance from the roadbed to the ceiling. The model width was set at 26 feet wide to mirror the lanes of traffic. The length was configured to assess the flow of the particulate in a 300 ft section immediately upstream of fan #3 beginning approximately 100 ft from the tunnel exit where the concentration would be the highest.

A traffic speed of 45 miles per hour or 66 feet per second from right to left was assumed and evaluated. To create a scale rate for the CO_2 flow, the overall required tunnel air rate was assessed by using the original design basis of 250,023 ft^3/min divided by the area of the roadbed of 78,000 ft^2 to determine an average constant rate of 3.2 $ft^3/min*ft^2$. In the model, an area of approximately 12,300 ft^2 was specified. The model area was configured in front of the fan to flow at a rate of 39,360 ft^3/min. A fan rate of 25,000 ft^3/min was chosen per the fan specifications as previously stated. The resulting velocity vector indicates a clockwise eddy current developing at the roadbed and continuing upwards toward the tunnel ceiling. The model does not account for the semispherical characteristics of the tunnel ceiling. The authors believe this will help the flow converge towards the fan inlet. The vector field analysis results in **Figure 8** appear to be concurrent with higher pressure that develops from the energy of the passing traffic.

The fan shows a significant increase in local velocity, but it does not seem to reflect a large outreaching pattern from the roadbed to the suction, as depicted in **Figure 9**. The suggestion that the fans would only be effective with the passing traffic is further proof that the effectiveness of the overall system is dependent on the displacement energy of available traffic.

One of the many variables in this project is that the CO_2 concentration of the tunnel is constantly changing throughout the day. The models generated by PyroSim require more than 3 hours of computational time for every 60 seconds of

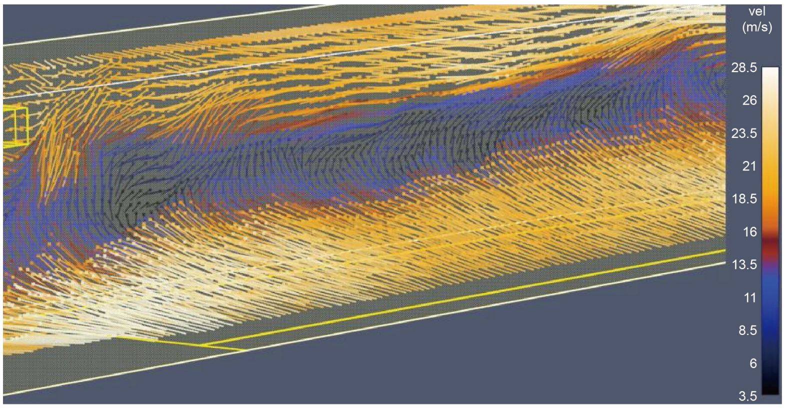


Figure 8. Velocity vector field.

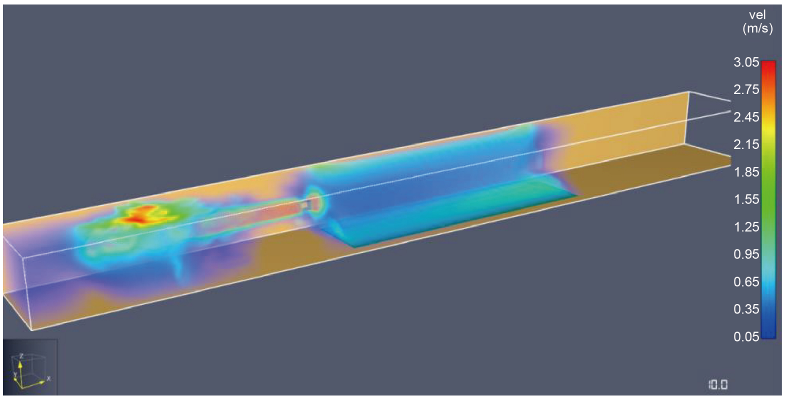


Figure 9. Velocity magnitudes.

model run time. The available density evaluation tool was utilized to evaluate density based on 1,200 ppm concentration to generate a preliminary rendering based on 60 seconds of run time, as shown in Figure 9. The results of this model indicate promising results that would be difficult to conclude without first attaining total developed flow from a period closer to 60 minutes of run time. The PyroSim model indicates that the initial flow is carrying the CO_2 particles towards the fan at a comparatively lower density within the first 60 seconds of run time (see Figure 10). Additional model runs reflected similar results.

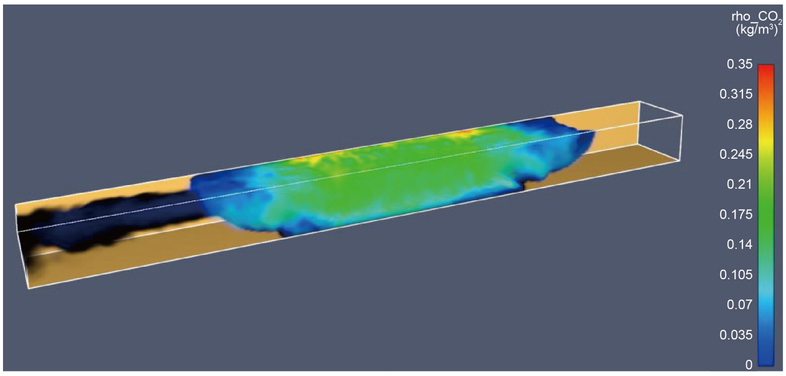


Figure 10. CO_2 density field.

3. Final Remarks

Tunnel ventilation and direct air capture (DAC) are two separate technologies but can be integrated to address environmental challenges, particularly in the context of air quality and carbon capture. In the case of the Wallace Tunnel located in the City of Mobile, Alabama, the tunnel has enough space to install a system above the roadbed to support an adequate ventilation and air capture combo. In this project, it was determined that the overhead space and structure worked well to allow for the suspension of the ducting system. If the space above the roadbed had been any more constricted, then smaller ducting would have been required, and as a result, it would have taken more power due to the increased losses.

DAC is an evolving technology and will continue to be limited by the amount of available capital to fund it. To help maximize capital impact, the CO_2 and VOC concentrations must be understood for the application area in question. Carbon capture projects that utilize tunnel ventilation should be focused on capturing CO_2 during the parts of the day when CO_2 concentration is at the highest. Additionally, when concentrations are highest the displacement energy of the passing traffic is also high, thus allowing for greater displacement of CO_2 particles from their source.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] AIE (2023) Alabama Fact Sheet. AIE State Rankings Report. https://chpalliance.org/wp-content/uploads/2016/10/Final_Alabama-Factsheet_AIE-State-Ranking-Report.pdf

[2] Climeworks (2010) Journey toward Net Zero with Climeworks' Carbon Removal Service. https://climeworks.com/?utm_source=googleBrand&utm_medium=cpc&utm_campaign=GS-AO-World-en-Brand&utm_term=climeworks&gclid=CjwKCAiAjrarBhAWEiwA2qWdCBnYc3phmgEn KOOBrVf3gPjWWGOsp-BxtGgqmhlop1JuEjb0Rfqn3RoCI08QAvD_BwE

[3] Carvel, R. and Marlair, G. (2005) A History of Fire Incidents in Tunnels. *Fire Safety Journal*, **40**, 325-344. https://doi.org/10.1680/hotfs.31685.0001

[4] Jiang, Y., Chen, Q. and Zhai, Z. (2019) Optimization of Ventilation Systems in Road Tunnels Using a Multi-Objective Genetic Algorithm. *Tunnelling and Underground Space Technology*, **92**, Article 103038.

[5] Choi, S., Drese, J.H. and Jones, C.W. (2009) Adsorbent Materials for Carbon Dioxide Capture from Large Anthropogenic Point Sources. *ChemSusChem*, **2**, 796-854. https://doi.org/10.1002/cssc.200900036

[6] Lee, J., Lee, S., Kim, S. and Kim, J. (2021) Recent Advances in Carbon Capture, Utilization, and Storage Technologies in Korea. *Clean Technologies and Environmental Policy*, **23**, 847-868.

[7] Mazzoldi, A., Rinaldi, A.P., Borgia, A. and Rutqvist, J. (2008) Geomechanical Modeling of the Effects of Carbon Dioxide Storage in Deep Saline Aquifers. *International Journal of Greenhouse Gas Control*, **2**, 434-445.

[8] Pini, R., Santoro, S. and Mazzotti, M. (2018) Binary Adsorption of CO_2/CH_4 and CO_2/N_2 on Dry Coals at High Pressure and Moderate Temperature. *Adsorption*, **15**, 303-315.

[9] Sanchez, D.L. and Kammen, D.M. (2016) A Commercialization Strategy for Carbon Capture, Utilization, and Sequestration. *Greenhouse Gases*: *Science and Technology*, **6**, 159-168.

[10] Xu, J., Wang, Y. and Guo, Q. (2019) Intelligent Control of Tunnel Ventilation Systems: A Review. *Energy and Buildings*, **185**, 169-185.

[11] Zhang, X., Wang, Y. and Zhang, Y. (2020) Application of Carbon Capture and Storage Technologies in Highway Tunnels. *Transportation Research Part D*: *Transport and Environment*, **80**, Article 102251.

[12] Brimblecombe, P., Colberg, C.A., Cheng, Y., Gertler, A.W., Hwa, M.Y., John, C., *et al*. (2020) Pollutant Concentration Measurement and Emission Factor Analysis of Highway Tunnel with Mainly HGVs in Mountainous Area. *Tunnelling and Underground Space Technology*, **106**, Article 103591. https://doi.org/10.1016/j.tust.2020.103591

[13] ALDOT (2023) Alabama Traffic Data. TDM Public. https://aldotgis.dot.state.al.us/TDMPublic/