The Impact of Ventilation Systems on Air Quality in Underground Parking Structures

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Abstract

Garages contain many harmful pollutants, including particulate matter smaller than 2.5 micrometers (PM2.5). These particles are responsible for millions of premature deaths annually, underscoring the urgency of mitigating air pollution. This study addresses the increase in air pollution in underground parking garages due to automobile exhaust. A physical model is used to demonstrate the effectiveness of auto-adjustable ventilation systems to clear PM2.5 pollutants in a one-level underground garage. Results show the most effective setup for achieving optimal air clearance in the testing trials is operating a central exhaust along with intake fans at 50% capacity.

1.0 Introduction

The most problematic pollutants in a parking garage are CO, NO_2, and PM2.5. Specifically, these components of air pollution were responsible for an estimated 4.2 million annual premature deaths globally in 2015. In the U.S., every increase of 10 $\mu g/m^3$ of PM2.5 is associated with a 3.4% increase in daily mortality, causing 52,000 annual premature deaths (Nazarenko et al., 2020).

According to a recent report from Swiss technology firm IQAir, only 13 countries met the World Health Organization's (WHO) recommended clean air standards. Only 17% of high-income countries and less than 1% of low- to middle-income ones meet the PM guidelines (Grant, 2023; World Health Organization, 2022a). The statistics underscore the need for air quality control regulations, particularly targeting high PM concentrations in underground garages.

1.1 Background

PM2.5 (particulate matter with a size of 2.5µm or smaller) can be a particularly damaging respiratory pollutant, infiltrating deep into the lungs, often resulting in irritation, damage to the alveolar wall, and a decline in lung function (Xing et al., 2016). Enclosed garage spaces allow these pollutants to accumulate, leading to a higher concentration of PM2.5, resulting in greater health issues for humans.

1.1.1 Passive vs Active Ventilation

To regulate airflow in buildings, passive or active ventilation systems are employed, controlling air quality, temperature, and humidity.

Passive ventilation utilizes **natural** airflow and structural design to manage indoor air quality. Techniques like pressure differences, the stack effect, and cross-ventilation leverage natural forces to circulate air. Pressure differences arise from changes in airflow shaft size, where smaller diameters increase velocity and decrease pressure [*Figure 2*]. The stack effect occurs as warm air rises and exits through high openings, drawing cooler air in through lower ones [*Figure 3*]. Cross ventilation results from outdoor wind pressure driving air through one side's openings and exiting through the opposite side [*Figure 4*].

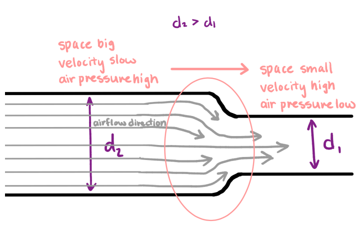


Figure 2: pressure differences

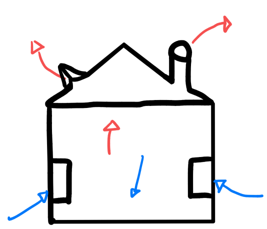


Figure 3: the stack effect

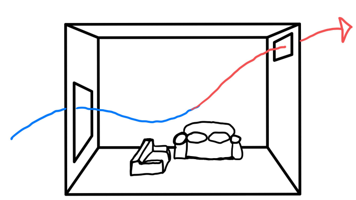


Figure 4: cross ventilation

Active ventilation employs **mechanical** systems—fans, blowers, or shafts—to control airflow and air quality. Mechanical fans create positive or negative pressure, based on fluid dynamics principles, to draw in clean air and expel pollutants [*Figure 5*].

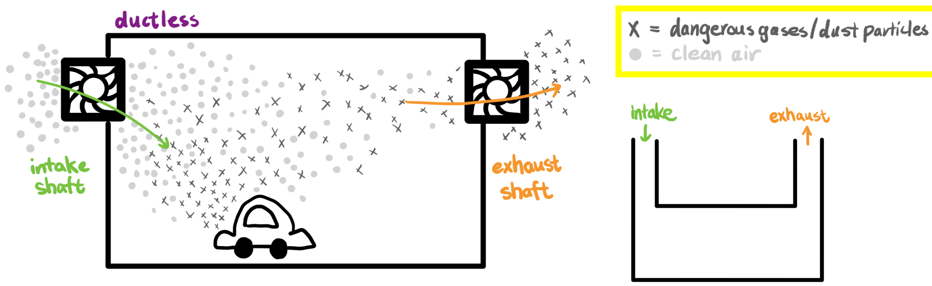


Figure 5: mechanical fans (fans only)

Additionally, sensors and feedback mechanisms maintain temperature and humidity levels, exchanging indoor and outdoor air efficiently by adjusting fan speeds based on air quality changes in specific zones.

For all underground garages, passive ventilation alone is insufficient. Current construction codes mandate active ventilation systems to eliminate hazardous pollutants (J. Tran & A. Gupta, personal communication, October 13, 2023).

1.1.3 Intake and Exhaust Shaft

Ventilation systems in enclosed or underground spaces rely on intake and exhaust shafts for effective air circulation, ensuring fresh air enters while polluted air exits.

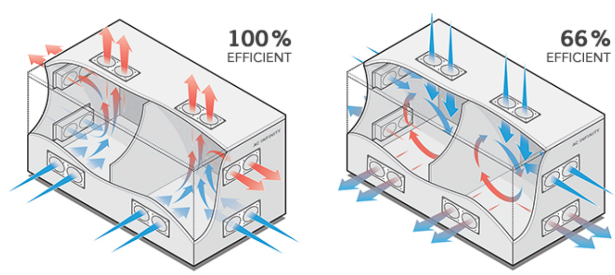


Figure 6: Optimal Cabinet Fan Configurations and Positioning (ACInfinity, n.d)

The intake shaft, typically positioned near the garage entrance, draws outdoor air using fans creating negative pressure in the garage. The airflow rate is managed with adjustable louvers or fans. Similarly, the exhaust shaft is located away from the entrance and expels stale air.

Exhaust fans that are positioned higher will leverage natural convection to optimize air movement [*Figure 6*]

It is not common for filters to be used in garage ventilation as the main purpose of the shaft is to circulate the clean air in and polluted air out rather than filter the air (J. Tran & A. Gupta, personal communication, October 13, 2023).

1.1.4 Ducted vs Non-ducted Systems

In underground garage ventilation, two main options are ducted and non-ducted systems. Ducted systems use a network of ventilation ducts for controlled airflow and pollutant extraction, keeping exhaust air separate from the air within the inner space where the car travels [*Figure 7*]. Conversely, non-ducted systems move air within the existing space, mixing exhaust air with garage air, requiring all the garage air to be moved. Jet fans are common in ductless ventilation systems as a method of moving large amounts of air quickly [*Figure 8*].

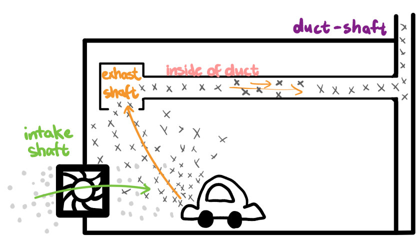


Figure 7: ducted system - shaft

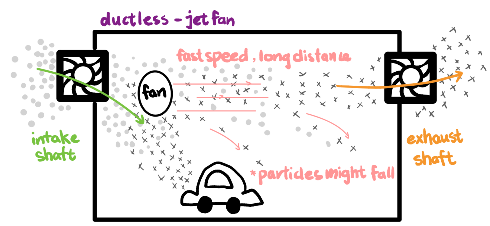


Figure 8: ductless system - jet fan

Choosing between these systems depends on factors like garage size, layout, and ventilation needs. Ducted systems offer precise control for larger, complex garages, while non-ducted systems are simpler and more cost-effective for smaller spaces. However, non-ducted systems may struggle with efficiency in larger areas due to limited airflow control. The choice should match specific garage requirements and design considerations(Aireserv, 2024).

1.2 Literature Review

1.2.1 Passive Ventilation Ducted Structure Design

A study done by Chu and Su in 2023 utilizes Computational fluid dynamics(CFD) to model the optimized design of passive ventilation systems for underground parking garages. They conclude that larger openings are required at the bottom and intermediate levels compared to the top level of multi-story garages. Case B3, shown in *Figure 9*, is the optimal structure according to the report result. The diagonal design of the ventilation shaft and the driveway could increase the ventilation rate by increasing the circulating flow inside the garage to remove the concentrated particles more effectively. The report also suggests that the garage should have a windcatcher(intake shaft) (Case A, seen in *Figure 9*) at each corner to allow the clean air to enter in different directions.

The conclusion provided by the study would be the crucial consideration for the design of the model garage in this report.

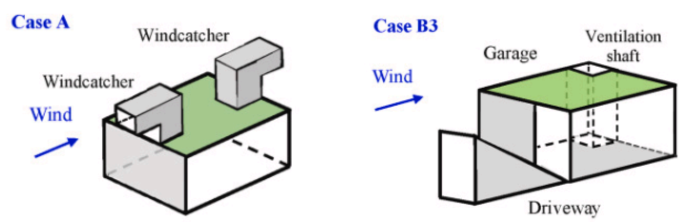


Figure 9: Schematic diagrams of underground garages with different ventilation designs

1.2.2 CO detector and auto-adjusting fans

Many garage ventilation systems now incorporate sensors to detect CO or other gasses, activating fans only when needed, saving 80-90% of energy (Popal, 2019). However, these sensors require frequent calibration and replacement, posing safety risks and energy waste when they malfunction.

1.2.3 Average Concentration of Indoor and Outdoor PM in Parking Garages

The study by Oh et al. (2020) states that most underground parking garages still rely on natural ventilation due to high energy consumption costs. However, these garages cannot ensure air quality indoors, resulting in elevated pollutant accumulation and health hazards. Their study assesses PM and total volatile organic compound(TVOC) levels, considering ventilation methods, traffic, and weather. Larger garages may have higher PM concentrations, especially when relying on natural airflow overnight. Efficient ventilation tailored to garage size is essential for energy conservation. The experiment shows the average annual indoor and outdoor PM concentrations, with indoor PM2.5 averaging 75-100 $\mu g/m^3$ across seasons. The data underscores the seriousness of health risks and provides the expectation of a safe air quality standard for projects.

1.3 Problem Statement

Flexible intake and exhaust systems are commonly used to control air circulation (specifically PM2.5) in parking structures. In a flexible system, each exhaust fan is connected to a sensor to evaluate the local air quality. When air quality reaches a trigger value, the local fan will run. This project will investigate the effectiveness of localized sensors and localized exhaust in keeping air clean in **all areas** of a one-level garage.

2.0 Method

This project will use an underground garage physical model and Arduino IDE and *Grove-Laser PM2.5 Sensor (HM3301)* to evaluate the air quality. Incense sticks are used as the source of PM because they generate consistent smoke. The position of the exhaust fans and on/off timing are adjusted for various experimental scenarios.

2.1 Air Quality Sensor

An Arduino Uno and *Grove - Laser PM2.5 Sensor (HM3301)* comprise the air quality detection device. The system is able to detect real-time air quality from three independent sensors and record data onto SD cards. Data from each sensor is synchronized.

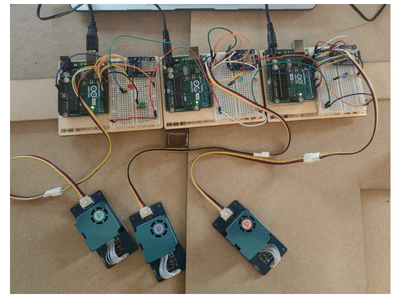


Figure 10: PM2.5 Detecting device

2.2 Garage Model

The garage model consisted of a 0.91m x 0.61m box made with medium-density fiberboard and acrylic plastic [*Figure 11*]. This garage size is a scale model for a typical small underground garage of 45.5m x 30.5m, which could hold about 120 cars. Three levels were constructed, including three exhaust fans on the ceiling of each level and two intake fans in diagonal positions. There are columns on each layer, and the small layer within each level represents the duct system on the ceiling of an underground garage. These layers can be slid in and out flexibly.

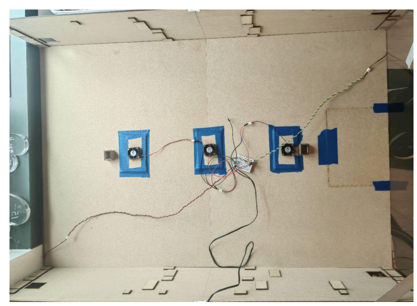
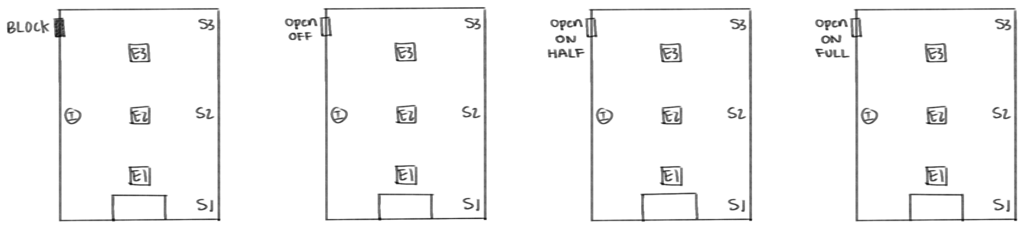


Figure 11: Garage Model

2.3 Experiment

Since the primary study was to investigate dead zones, an incense stick was placed in the middle of the left side as the source of pollution; the sensors (S1, S2, and S3) were located on the right side of the garage. An entrance ramp was left open to the air as the source of clean air (shown on the bottom, center of Figure 12). A single intake is located at the left-side corner away from the ramp.

Four experimental trials will be carried out with different settings of the intake fan: intake closed, intake open-fan off, intake open-fan 50% on, and intake open-fan 100% on[*Figure 12*].



I = incense
□ = intake
E = exhaust
S = sensor

Figure 12: testing trials

For each experimental trial, the following process was implemented, see *Figure 13*. Each test allowed the garage to fill with smoke, then each local exhaust fan turned on in sequential order E1 on - off, then E2 on - off, and lastly E3 on - off. For each trial, the intake fan capacity was set to: blocked, open - off, open - 50% on, and open - 100%.

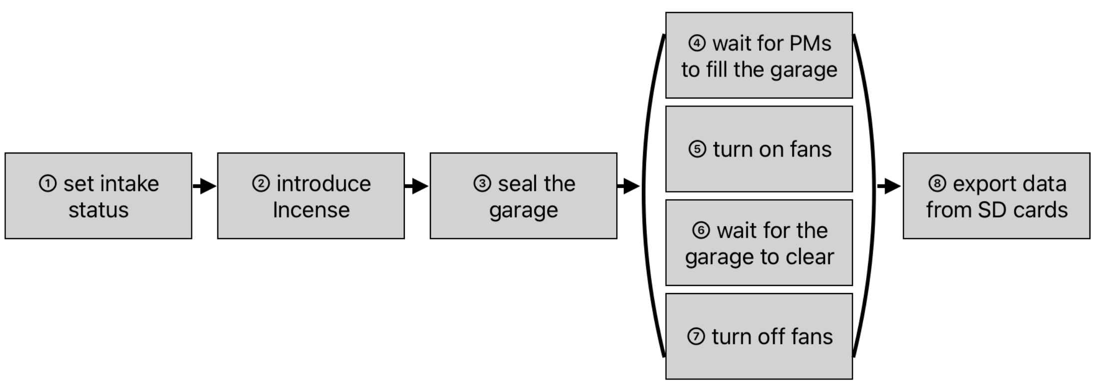


Figure 13: testing procedures

3.0 Result

For experiment 1 (intake fan closed), Figure 14 shows a plot of PM2.5 level when each exhaust was turned on. Notice areas monitored by S1 and S2 are cleared of PM2.5 regardless of which exhaust fan is used. S3 shows a decrease in PM2.5 but only gets clear when all three exhausts are on S3 representing a dead zone in this configuration.

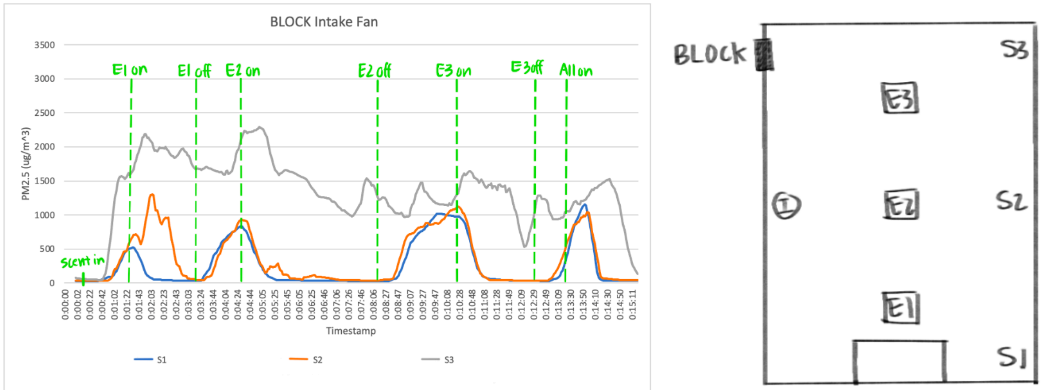


Figure 14: Intake Vent Closed - Fan Off

For experiment 2 (intake open - fan off), E1 shows a decrease in all three sensors but didn't fully clear. S3 still shows a decrease in PM2.5, but it never completely clears even when all three exhausts are on. Notice a short increase in PM2.5 levels of the dead-zone area when the exhausts are turned on in both *Figure 14* and *Figure 15*.

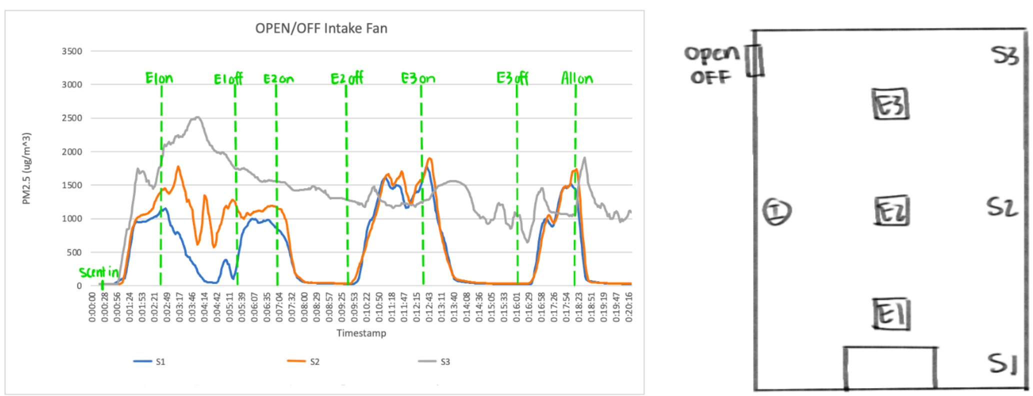


Figure 15: Intake Vent Open - Fan Off

Experiment 3 (intake open - fan 50% on) shown in Figure 16 demonstrates all areas are cleared (including the dead zone of S3) regardless of which exhaust fan is used. Note that this chart shows the E1 trial being tested twice, with the second test manually aborted before the air fully cleared.

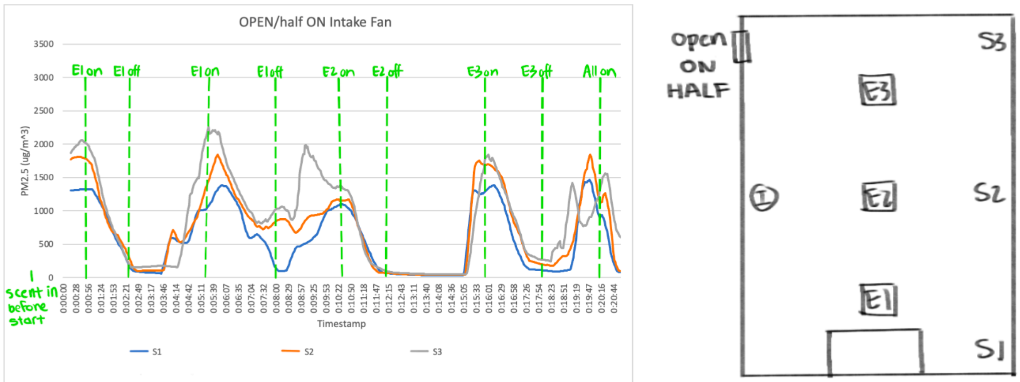


Figure 16: Intake Vent Open - Fan On 50%

Experiment 4 (intake open - fan 100% on) shows in Figure 17 that none of the areas are fully cleared. The overall PM2.5 when the exhaust is turned on is about 500 µg/m^3.

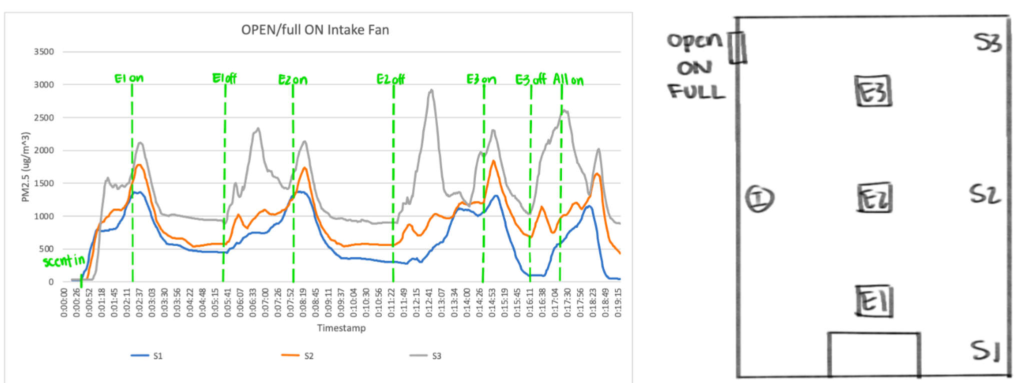


Figure 17: Intake Vent Open - Fan On 100%

4.0 Discussion

Intake Configuration	**Sensor 1**	**Sensor 2**	**Sensor 3**	**Note**
Closed	cleared	cleared	no	Only the ramp opening is not sufficient as an intake.
Open	cleared	cleared (expt. E1)	no	Only the ramp and intake opening are still not sufficient to clear the dead zones.
Open + 50% fan	cleared	cleared	cleared	The intake is open and 1/2 on + any single exhaust will clear the air.
Open + 100% fan	no	no	no	Too much intake causes turbulent air flow and does not clear air.

Figure 18: Clearance Summary

4.1 Data Analysis

This experiment demonstrates the presence of a dead zone in the farthest corner, indicated by the small decrease in the gray line. Additionally, PM2.5 levels continued to rise after the exhaust was turned on, probably because of the remaining airflow current caused by the exhaust. The data underscores the safety concern associated with the corner furthest from the ramp.

Even if the intake fan close to the dead zone is opened, the dead zone corner still doesn't get cleared. Despite all three exhausts being activated, the S3 corner remains uncleared, which might be caused by the airflow from the open intake, preventing the exhaust from pulling the air out from the S3 corner. Notably, the overall PM2.5 level is higher than when the intake is closed. This could be attributed to the intake hole promoting faster airflow, resulting in quicker PM dispersion to its peak level.

The air in the location for all three sensors gets clean, including the dead zone. When the fans were off, polluted air was distributed faster than the other tests, probably due to the continued circulation of air provided by the intake fan.

The overall PM2.5 level is the highest among the four tests. The graph shows a very clear relationship between the level of PM2.5 at each location. PM2.5 level: S3>S2>S1 all the time, which could be the result of turbulent airflow. The lowest PM2.5 level, 100-500 $\mu g/m^3$, is still too much, compared to the recommended annual indoor PM2.5 averaging 75-100 $\mu g/m^3$ across seasons (see section 1.2.3).

Overall, it is essential to regulate the intake fan at an appropriate rate, determined by the specific characteristics of the garage, necessitating a series of tests for optimal performance calibration.

4.2 Limitations

While efforts were made to completely seal the garage from leaks to simulate an underground scenario, small leaks may still occur where the sensor wires entered the model. Moreover, the scale between the incense stick and the size of the model is important. The rapid diffusion of smoke in such a small model makes it difficult for the sensors to detect the sequence of smoke progression. When the smoke level exceeds the detecting range of the sensor, the data is not reliable. This happened when the sensor was placed next to the incense stick, which caused false readings.

4.3 Future Work

Currently, the tests only focused on a one-level garage. However, exploring the effectiveness of the auto-adjustable ventilation system across multiple levels would be a valuable area for future investigation. Additionally, developing a program to detect PM changes and simultaneously adjust the fan rates or turn them on/off would also be a worthwhile endeavor.

5.0 Conclusion

PM2.5 is considered to be a dangerous particle that severely impacts the function of human respiratory systems, especially in underground garage environments. This study produced a model garage for single-level air quality testing that can be expanded to three levels. Ventilation testing showed the optimal air clearance combination within testing trails is using a central exhaust along with an intake fan operating at 50%.

5.1 Acknowledgements

Thanks to Mr. Ty Buxman and Mr. Bruce Waggoner for their help and support throughout this project, both during class and after school. Thanks to Charlotte Zhong for making the fan pieces. Thanks to Flintridge Sacred Heart Academy for providing the space and materials.

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