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Invention of a new device to optimise air quality for vehicle occupants in Sydney's tunnels: the Car Canary

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ABSTRACT

Traffic-related air pollutants (TRAP) present a risk to vehicle occupants (VO) when driving in tunnels. Recirculating vehicle cabin air (RVCA) is the current recommended strategy to protect motorists from TRAP exposure. TRAP and carbon dioxide (CO_2) concentrations were hypothesised to be higher in tunnels, with RVCA reducing TRAP but increasing exposure to CO_2. Air quality testing in tunnels confirmed the presence of TRAP and that CO_2 accumulates in a passenger vehicle when two VO use RVCA. The measured levels of CO_2 indicate poor ventilation and a build up of re-breathed air, which may increase the risk of transmission of airborne viruses when an infectious person is present, along with fatigue or drowsiness that may be relevant to driving behaviour. Three scenarios were tested using different combinations of RVCA and window use. Testing indicated a trade-off: particulate matter 2.5 µm or less in diameter ($PM_{2.5}$) exposure was highest with windows open and lowest with windows closed and RVCA enabled, while CO_2 exposure was highest when RVCA was enabled. Driving with windows closed and RVCA disabled reduced CO_2 exposure but slightly increased $PM_{2.5}$ exposure. To help manage this trade-off, a prototype device known as the Car Canary was developed to alert VO when $PM_{2.5}$ reaches a set point, indicating when to enable RVCA. These preliminary findings from the WestConnex M4–M8 tunnel system suggest that closing windows while using the device to guide RVCA use may help balance exposure to CO_2 and TRAP, although further research is needed. This proof-of-concept device, known as Car Canary was invented and successfully tested in this pilot study.

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YASJ Editors' Note: This study combines environmental measurement with engineering design to investigate air quality in Sydney road tunnels and develop the Car Canary prototype. The progression from sensor comparison to a functioning proof-of-concept device is a particular strength. Readers should note that testing used a single vehicle with two occupants and a relatively small number of replicates, while the low-cost CO_2 sensor showed poor agreement with the research-grade instrument. The findings are therefore preliminary, but provide a strong basis for further testing and development.

INTRODUCTION

Vehicle usage in Australia is increasing, with the largest number of registered vehicles being in New South Wales (NSW) (Australian Bureau of Statistics, 2016, 2022). Emissions from motor vehicles are termed "traffic-related air pollutants" (TRAP) which are associated with adverse health

effects including asthma and cardiovascular disease (Health Effects Institute, 2010). Vehicle occupants (VO) are exposed to the highest concentrations of TRAP within road tunnels (Knibbs et al., 2009; Martin et al., 2016; Morawska et al., 2008). Recirculating vehicle cabin air (RVCA) is one strategy recommended to minimise exposure of TRAP to VO (Transport for NSW, 2023), however RVCA increases the concentration of exhaled carbon dioxide (CO_2). This increases the risk of infection of airborne viruses such as COVID-19 if an infected VO is present (Peng & Jimenez, 2021) and can cause detrimental effects to cognitive function, leading to effects on decision making and poor driving ability (Jung et al., 2017; Satish et al., 2012). Therefore a balance is needed to provide optimal air quality conditions to VO (Kumar et al., 2021).

Although there is a need to mitigate health risks for VO, at present there are no systems or devices developed that balance the risks of exposure to TRAP, CO_2 and infection risk to VO in tunnels. This literature suggests that VO would benefit from the development of a simple yet sensitive device that could alert occupants when it is appropriate to disable RVCA (Kumar et al., 2021).

It was hypothesised that concentrations of both TRAP and CO_2 would be higher inside the tunnel than they would be in non-tunnel environments. Additionally, it was anticipated that VO would be most protected from TRAP when using RVCA and would be most protected from CO_2 when RVCA was turned off. It was also anticipated that $PM_{2.5}$ exposure would be highest when driving with windows open and lowest when driving with windows closed and RVCA enabled, while CO_2 exposure would be highest when RVCA was enabled. In addition, it was hypothesised that a home-made engineered device (HMED) would accurately measure in-vehicle air quality and alert VO at an appropriate time when RVCA should be used to maximise VO health and safety.

MATERIALS AND METHODS

Testing occurred in Sydney's longest section of road tunnel, being the WestConnex M4–M8 system, a 22.km expressway and involved five phases.

Phase 1: Obtaining and constructing monitoring devices

Components were sourced to build a HMED that contained relevant air quality parameters to measure TRAP and CO_2. The HMED was constructed from readily accessible Arduino-compatible components and included particulate matter, particularly fine particles $\leq 2.5\,\mu m$ in diameter ($PM_{2.5}$), nitrogen dioxide (NO_2), and CO_2 sensors. Wires and sensors were secured to the circuit board through soldering. The entire unit was built into a small plastic lunchbox container to keep it secure.

Research grade devices (RGDs) measuring the same parameters were also sourced. These included the Thermo Fisher Scientific Personal DataRAM pDR-1500 monitor, the Honeywell ToxiRAE Pro and the Aranet4 monitor. The aim of using RGDs was to determine the accuracy of the HMEDs and how they correlated to the measurements collected from RGDs.

The HMED and RGDs were placed inside a cardboard box which was placed in the researcher's lap in the passenger seat. Devices were secured to the box with a putty-like adhesive to prevent movement during testing.

Phase 2: In-field test

The HMED and RGDs were used to measure air quality while a vehicle was driven along various testing routes including tunnel and non-tunnel environments.

The researcher performed all measurement activities, while a second VO drove the vehicle which was a 2023 model Volkswagen T-Cross that was powered by regular unleaded petrol. To mimic the typical activities of commuters, testing was undertaken during peak hour.

Seven different routes were used (Table 1). The route taken was determined by the type of test being conducted. Route 1 or 2 involved tunnel testing while non-tunnel (control) testing occurred in Routes 3 to 7. The purpose of control testing was to determine whether air quality inside the tunnel differed from air quality outside the tunnel.

Each device was calibrated before use in accordance with manufacturers instructions. Prior to entering the tunnel, for all tests, the air-conditioning (AC) was turned on, RVCA was turned off and all windows were opened to venti-

Table 1. Testing routes

Route	Start and finish location	Type of route
1	Sydney Olympic Park Aquatic Centre (SOPAC) to Kingsgrove	Tunnel
2	Kingsgrove to SOPAC	Tunnel
3	SOPAC to Balmain	Non tunnel
4	Balmain to SOPAC	Non tunnel
5	Kingsgrove to Balmain	Non tunnel
6	Balmain to Kingsgrove	Non tunnel
7	SOPAC to Kingsgrove	Non tunnel

late the car. VO wore P2 respirators to protect themselves from TRAP during all tests. Upon entry to the tunnel, the time was recorded. An overview of how each tunnel test was carried out is shown in Table 2.

The mitigation strategies listed in Table 2 in the control tests were active upon commencement of the test. For the in tunnel tests, these strategies were active upon entry of the tunnel system. Between 3 to 7 replicates were completed per test.

The data obtained from each device were downloaded after each testing day and analysed in Microsoft Excel.

Phase 3: Preliminary analysis

To compare the control and experimental values received for both CO_2 and TRAP, a T-test for each treatment was performed to determine whether there was a difference between air quality inside and outside of tunnels. Regression analysis determined whether there was a true correlation between measurements collected from the RGD and HMED for each parameter and treatment.

Microsoft Excel was used to perform the analysis and to graph the results.

The parameter in the HMED that most closely correlated to the RGD was selected by comparing the Correlation Coefficient.

The CO_2 concentrations recorded while using RVCA were analysed to determine the average time it took for CO_2 to reach levels that presented a risk to VO.

The results of the statistical analysis were used to select the TRAP parameter that had the closest correlation between the HMED and RGD for use in an improved HMED.

Phase 4: Device construction

Statistical analyses calculated a line of best fit between the HMED parameters and the RGD. That line of fit provided a correction equation which became the code put into the software of an improved prototype device so that the measurements displayed would be corrected to be as close as possible to the measurements from a RGD.

An alarm value was also coded into the software so that the new prototype device would turn on a LED light at a specific set-point. The purpose of the light was to alert VO when to turn RVCA on or off. All coding was performed in Arduino.

The device was improved to be a compact unit that could be safely used in a vehicle. A yellow case was 3D printed and used to house all components. This improved HMED was given the name the "*Car Canary*".

The initial HMED was constructed as shown in Figure 1. All phases were completed between April and August 2024.

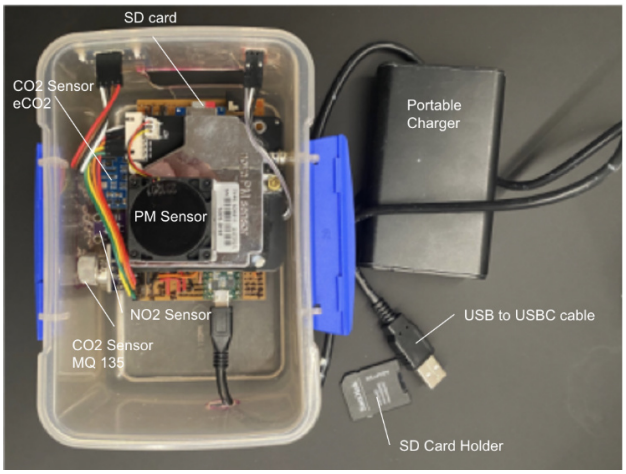


Figure 1. Home-made engineered device (HMED).

Table 2. Purpose of performing each test type

Test	Mitigation strategy	Measuring
A	Windows Open, AC on	TRAP in tunnel
B	Windows Closed, AC on, Fresh Air	TRAP in vehicle in tunnel
C	Windows Closed, AC on, RVCA	CO_2 in vehicle in tunnel
Control A	Control: Windows Open, AC on	TRAP in road
Control B	Control: Windows Closed, AC on, Fresh Air	TRAP in vehicle in road
Control C	Control: Windows Closed, AC on, RVCA	CO_2 in vehicle in road

Phase 5: Device testing

Both the *Car Canary* and the RGD were used to measure air quality in parallel both inside and outside of tunnels. A regression analysis was performed on the data from the *Car Canary* and the RGD to determine whether the results were highly correlated.

To validate and check accuracy, the *Car Canary* was exposed to concentrations above the alarm value to determine whether the LED light turned on at the specific set-point.

Ethics approval for this study was obtained from the school's Ethics Committee in March 2024.

RESULTS

A total of 35 tests of the HMED and RGD were completed in peak hour across various testing routes. Testing was done with the windows open (Test A); windows closed with RVCA disabled (Test B); and with windows closed with RVCA enabled (Test C). Between 3 and 7 replicates of each test were completed.

A review of the trends and the maximum concentrations recorded showed that concentrations of $PM_{2.5}$ rose steadily when driving through the tunnels with windows open or when RVCA was disabled with concentrations decreasing rapidly upon exiting the tunnel. Conversely, concentrations of $PM_{2.5}$ decreased when RVCA was enabled at the start of the trip and increased when RVCA was disabled. The highest concentrations of $PM_{2.5}$ were during Test A (windows open, AC on, in tunnel), and the lowest concentrations were during Test C (windows closed, AC on, RVCA, in tunnel).

Figure 2 displays the average of the maximum concentration of $PM_{2.5}$ for each set of tests recorded by the RGD.

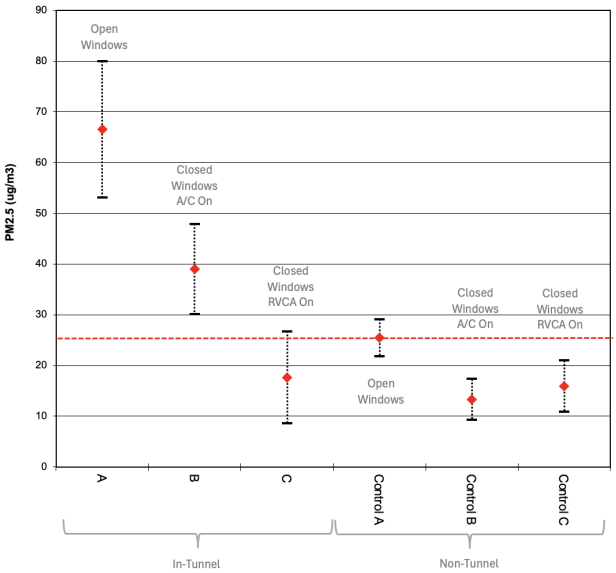


Figure 2. Average maximum concentrations of $PM_{2.5}$ recorded in each test (RGD). The error bars represent one standard deviation. The red line represents the 24-hour trigger limit of $25\,\mu g/m^3$ for $PM_{2.5}$. Values represent $n = 3$–7 replicates per test type.

The maximum concentration of $PM_{2.5}$ exceeded the 24-hour trigger level during Test A and B. During Test A and Test B, it took an average of 6 and 12-minutes respectively to exceed the 24-hour trigger level.

A review of the trends and maximum concentrations recorded in each test was performed for the HMED. Consistent with the RGD, concentrations of $PM_{2.5}$ rose steadily when driving through the tunnels with windows open or when RVCA was turned off with concentrations decreasing rapidly upon exiting the tunnel. Concentrations of $PM_{2.5}$ also decreased when RVCA was turned on and increased when RVCA was disabled. The highest concentrations of $PM_{2.5}$ were during Test A and the lowest concentrations were during Test C (Figure 3).

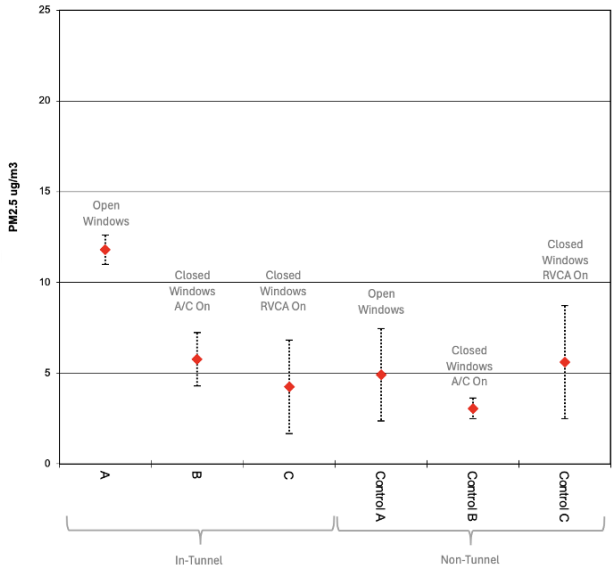


Figure 3. Average maximum concentrations of $PM_{2.5}$ recorded in each test (HMED). The error bars represent one standard deviation. Values represent $n = 3$–7 replicates per test type.

Similar to the RGD, the concentrations of $PM_{2.5}$ measured by the HMED were higher while driving in the tunnel with windows open than they were when RVCA was used. The highest concentrations of $PM_{2.5}$ were during Test A and the lowest concentrations were during Test C.

CO_2 measurements

CO_2 was successfully measured by the RGD and HMED. A review of the trends and the maximum concentrations recorded in each test was performed and showed that concentrations of CO_2 rose during all tests while driving through the tunnel or when RVCA was used. This includes with windows open (Test A), with air-conditioning on and no RVCA (Test B) and with air-conditioning on and recirculated air (Test C). Concentrations of CO_2 were the highest during Test C.

Figure 4 displays the average of the maximum concentrations of CO_2 recorded in each test by the RGD. The red lines represent the trigger limits of 800 ppm, 1000 ppm, and 3000 ppm for CO_2.

There were two CO_2 sensors in the HMED: an eCO_2 and MQ135 sensor. The MQ135 sensor recorded a value that correlates to CO_2 concentrations, however the recorded values had a minimal range (between 35 and 40) and did not change significantly between tests. These data were therefore excluded. The eCO_2 sensor was more sensitive and recorded measurements of CO_2 that ranged between expected ambient concentrations to over 2000 parts per million (ppm). The data from the eCO_2 sensor was included in this analysis.

A review of the trends and maximum concentrations recorded in each test was performed from the HMED. Consistent with the RGD, concentrations of CO_2 rose when driving in the tunnel or when RVCA was enabled. However, concentrations of CO_2 recorded by the HMED were higher in Test A and B compared to Test C.

Figure 5 displays the average of the maximum concentrations of CO_2 recorded in each test by the HMED. The red lines represent the trigger limits of 800 ppm, 1000 ppm, and 3000 ppm for CO_2.

In comparison to the RGD, the HMED did not show significantly different maximum concentrations of CO_2 while driving in the tunnel than when not in the tunnel, nor did it show the highest concentrations when RVCA was used.

Table 3 provides a summary of air quality tests conducted in the tunnel along with the average time it took in minutes to exceed the safety thresholds.

Statistical analysis

An F-test confirmed the control and experimental values of both $PM_{2.5}$ and CO_2 had an equal variance and supported the use of a two-sample t-test assuming equal variances.

The analysis demonstrated that there was a significant difference between Test A and Control A ($PM_{2.5}$ $p = 0.004$, CO_2 $p = 0.000003$) and Test B and Control B ($PM_{2.5}$ $p = 0.0001$, CO_2 $p = 3.3 \times 10^{-5}$). There was no significant difference between Test C and Control C ($PM_{2.5}$ $p = 0.8$, CO_2 $p = 0.3$).

An ANOVA was conducted for both parameters to determine if there was a significant difference between Test A, B and C. The analysis provided evidence to reject the null hypothesis of this statistical test ($PM_{2.5}$ $p = 0.000005$ and $F[30.2] > F_{\text{Critical}}[3.7]$; CO_2 $p = 0.00000002$ and $F[70.3] > F_{\text{Critical}}[3.7]$), indicating that there was a significant difference between the three tests in both parameters.

To determine where this difference was, a Tukey test was conducted on the average $PM_{2.5}$ between tests. The analysis showed there was a significant difference between each test type ($p < 0.01$). For CO_2, the analysis showed there was a significant

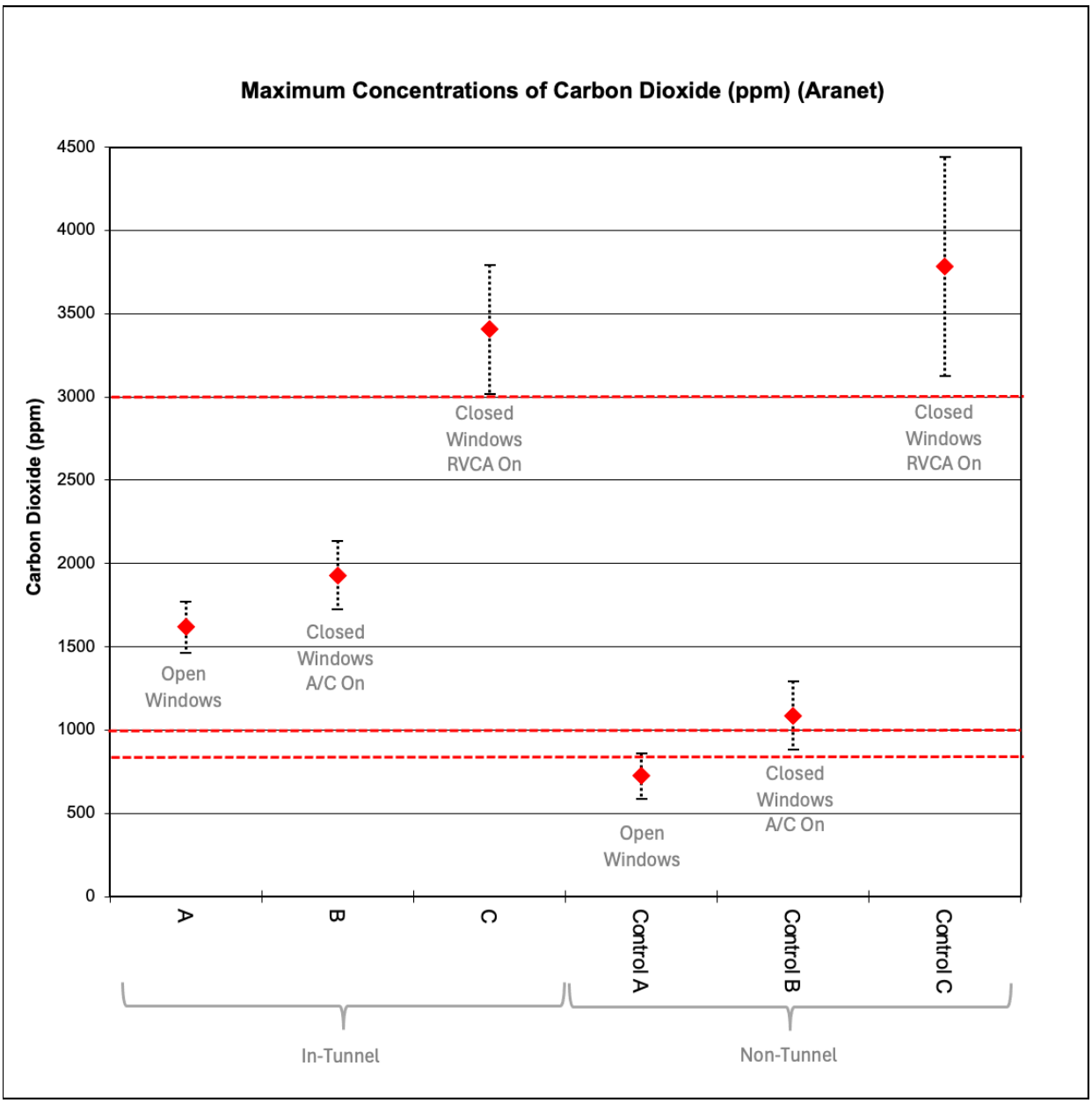


Figure 4. Maximum concentrations of CO_2 recorded in each test by the RGD. The error bars represent one standard deviation. Values represent $n = 3$–7 replicates per test type.

Table 3. Average time to reach threshold values for $PM_{2.5}$ and CO_2 under different mitigation scenarios (NR = not reached)

Parameter	Threshold	Windows Open (min)	Windows Closed RVCA disabled (min)	Windows Closed RVCA enabled (min)
$PM_{2.5}$	25 µg/m^3	6	12	NR
$PM_{2.5}$	50 µg/m^3	14	NR	NR
CO_2	800 ppm	7	2	3
CO_2	1 000 ppm	9	3	4
CO_2	3 000 ppm	NR	NR	16

difference between Test A and C ($p < 0.01$) as well as between Test B and C ($p < 0.01$) but not between Test A and B.

Therefore, there was a significant difference be-

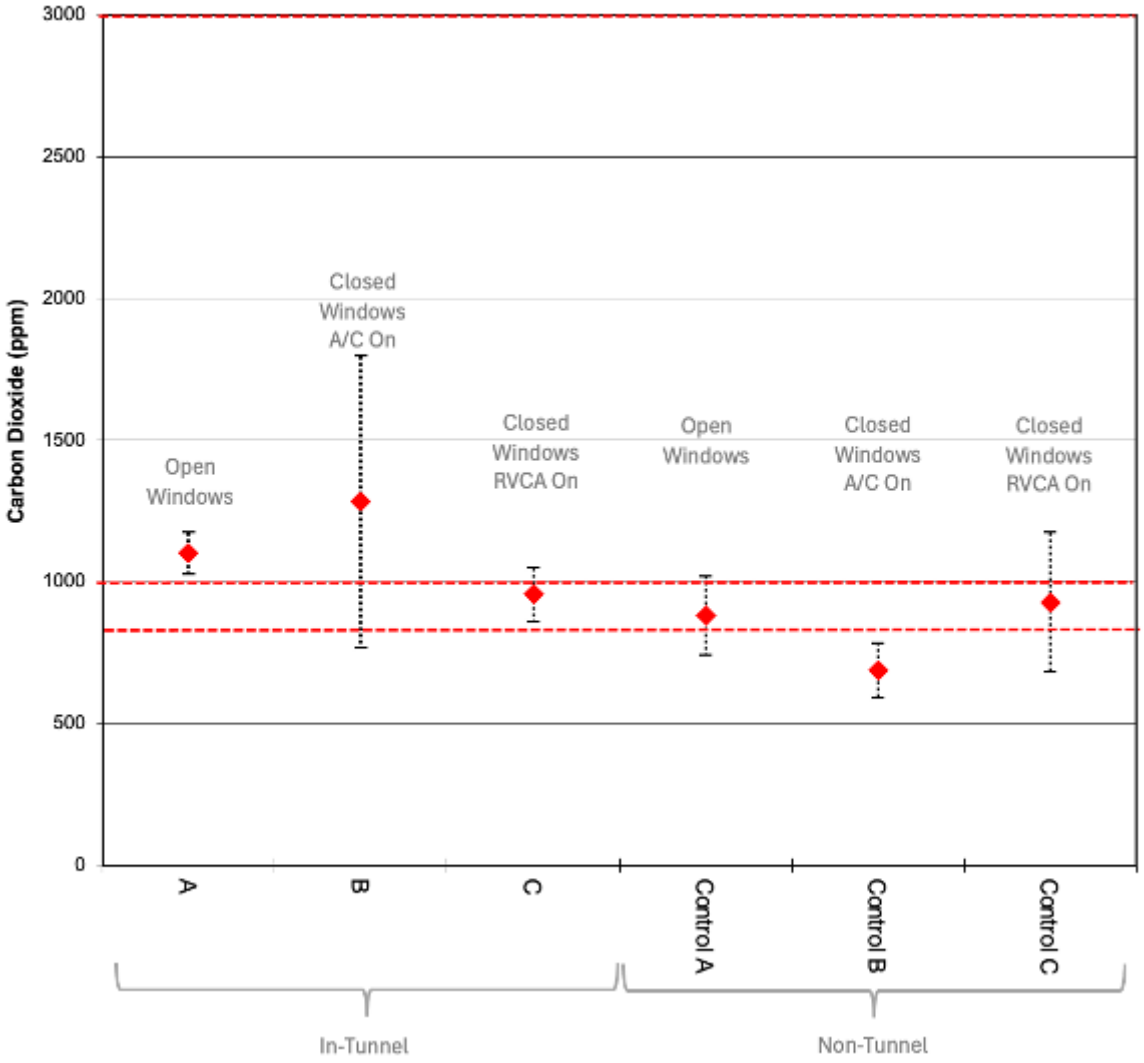


Figure 5. Maximum concentrations of CO_2 recorded in each test (HMED). The error bars represent one standard deviation. Values represent $n = 3$–7 replicates per test type.

tween $PM_{2.5}$ and CO_2 concentrations when driving through tunnels in comparison to a non-tunnel environment when windows were open (Test A) or closed (Test B) without RVCA. However there was not a significant difference between $PM_{2.5}$ or CO_2 concentrations inside the vehicle whether driving through a tunnel or non-tunnel environment when RVCA was used.

$PM_{2.5}$ remained below the threshold values in both tests. Further, the concentrations of $PM_{2.5}$ inside the vehicle were significantly different during each mitigation strategy. Concentrations of CO_2 when using RVCA were significantly different in comparison to when RVCA was disabled.

A regression analysis was performed on the $PM_{2.5}$ data collected from the RGD and the HMED from all Test A results (with outliers omitted). The RGD consistently recorded higher concentrations of $PM_{2.5}$ in comparison to the HMED, but the Pearson Correlation Coefficient was strong (Multiple $R = 0.89$) and the proportion of points that fit the regression line were also high ($R^2 = 0.80$). Figure 6 displays the results of the line of best fit. A regression analysis was performed on the CO_2 data collected from the RGD and the HMED from all Test C results. The RGD consistently recorded higher concentrations of CO_2 in comparison to the HMED. The Pearson Correlation Coefficient was low (Multiple $R = 0.31$) and the proportion of points that fit the regression line were also low ($R^2 = 0.10$). Figure 7 displays the results of the line fit plot.

The TRAP sensor in the HMED that most closely correlated to the scientific grade monitor was $PM_{2.5}$. Therefore it was this parameter selected for use in the improved HMED, known as the *Car Canary*.

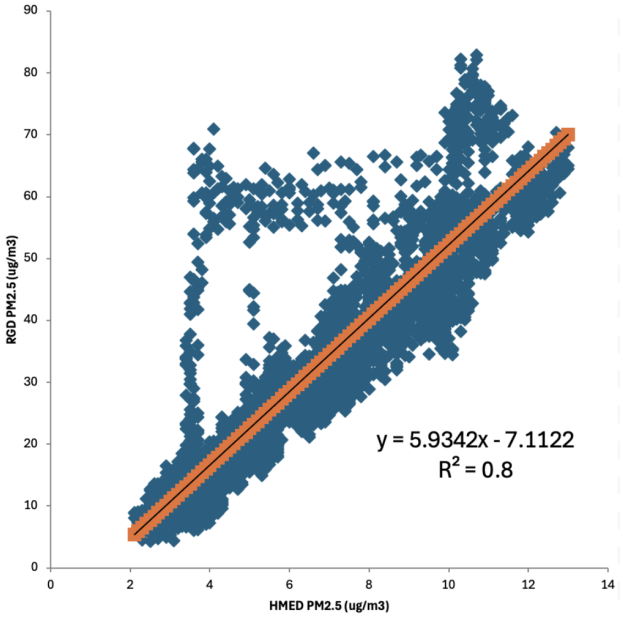


Figure 6. Line Fit Plot of $PM_{2.5}$ data for RGD and HMED measurements.

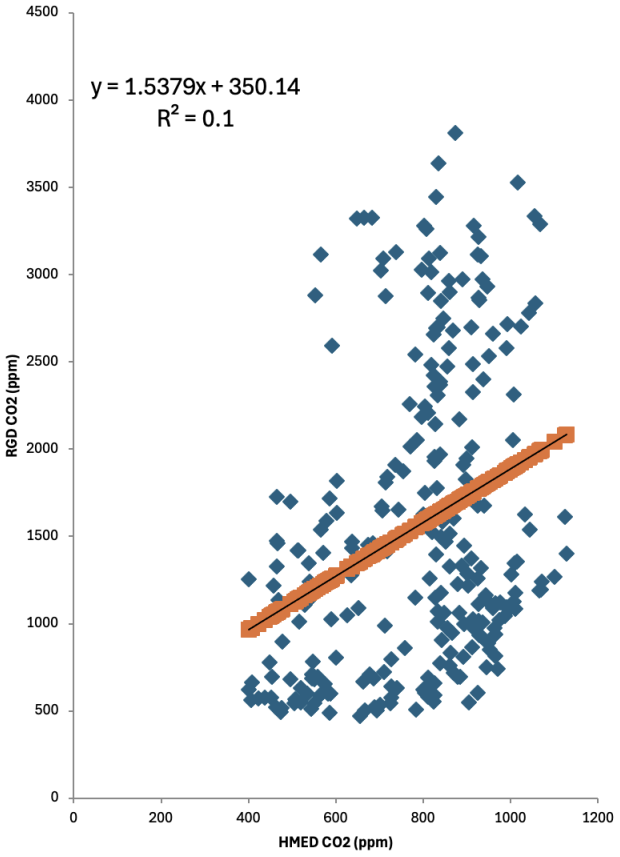


Figure 7. Line Fit Plot of CO_2 data for RGD and HMED measurements.

Car Canary prototype implementation

The Car Canary was upgraded and enhanced using the same low-cost $PM_{2.5}$ sensor as used in the initial testing. Other features included can be seen in Figure 8. The Car Canary was powered by an external USB charger which was connected via USB cable.

The formula below was programmed into the code in Arduino so that the measurements recorded by the $PM_{2.5}$ sensor in the *Car Canary* more closely aligned with the concentrations measured by the RGD:

$$\text{OUTPUT} = 5.9342x - 7.1122 + 8 \qquad (1)$$

where OUTPUT = numbers displayed and recorded by the *Car Canary*, and x = concentration measured by the $PM_{2.5}$ sensor in the *Car Canary*.

The formula was obtained from the line of best fit of $PM_{2.5}$ data and adding a value for the standard error. The standard error represents the value that the average calculated values were to the regression line of the data, which was 8 µg/m^3.

Other items included in the code in Arduino were to include a trigger limit of 50 µg/m^3. At that value, the Car Canary was programmed to turn on an LED light when $PM_{2.5}$ concentrations reached or exceeded 50 µg/m^3. To minimise the light turning on and off when $PM_{2.5}$ concentrations are near that limit, the measurements were programmed to run as a 10-second average. The value of 50 µg/m^3 was selected as a conservative measure to keep average exposures to VO below 25 µg/m^3. This is further explained in the discussion. A copy of the code can be provided upon request.

DISCUSSION

This investigation explored whether a HMED could monitor air quality and alert VO to enable or disable RVCA to minimize health risks. Testing focused on NO_2, $PM_{2.5}$, and CO_2 in tunnels. NO_2 was undetectable and excluded from analysis. $PM_{2.5}$ and CO_2 showed significant differences in air quality inside and outside tunnels with RVCA on or off.

It was found that:

- $PM_{2.5}$ concentrations were highest with win-

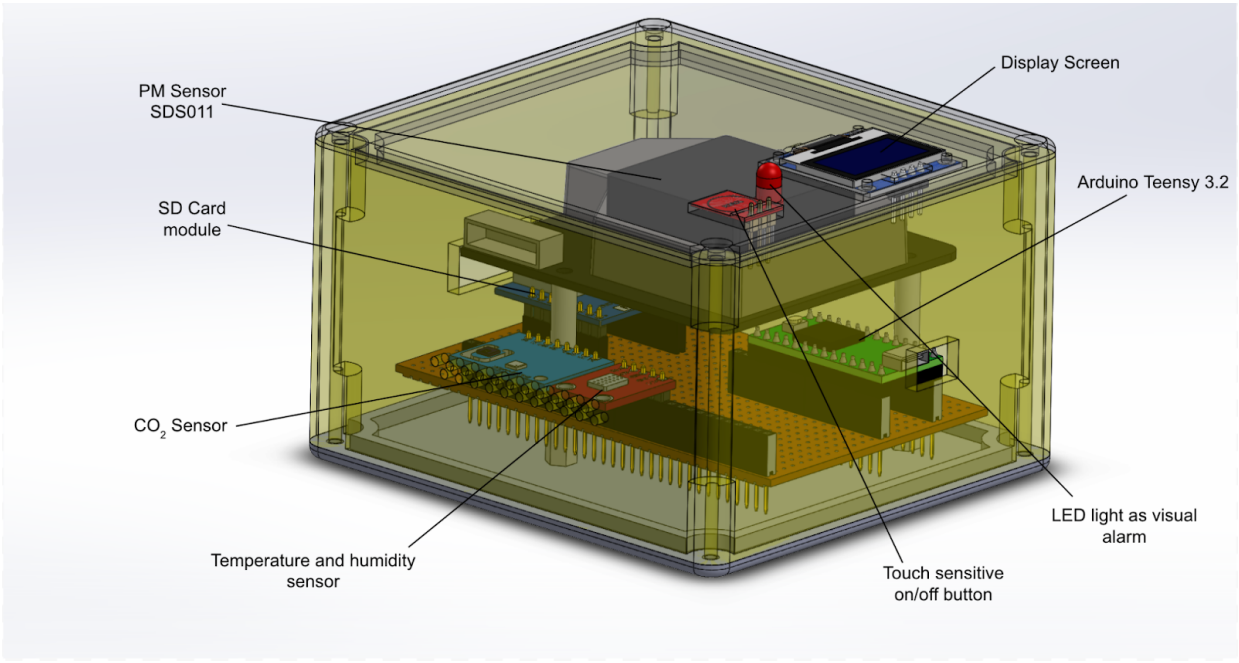


Figure 8. Car Canary layout and enclosure design.

dows open and lowest with windows closed and RVCA enabled, supporting the hypothesis that closing windows and enabling RVCA protects VO from TRAP exposure.

- CO_2 concentrations were highest with RVCA enabled and lowest with windows open. CO_2 levels exceeded trigger thresholds with RVCA enabled.
- A significant difference in CO_2 levels between Test A and Control A ($p < 0.05$) and Test B and Control B ($p < 0.05$) indicated additional CO_2 sources, likely vehicle exhaust. No significant difference was found between Test C and Control C ($p > 0.05$), confirming VO as the primary CO_2 source in those tests.

High CO_2 exposure is associated with risks of fatigue, and is a proxy for poor ventilation and re-breathed air. An increased infection risk arises from accumulation and recirculation of virus-laden aerosols when an infectious person is present. Reducing CO_2 exposure may therefore be beneficial. TRAP is also associated with adverse health effects including asthma and cardiovascular disease (Health Effects Institute, 2010). Disabling RVCA while keeping windows closed and AC on fresh air reduced CO_2 exposure but slightly increased $PM_{2.5}$ exposure.

In regards to device effectiveness, the $PM_{2.5}$ sensor in the HMED closely matched scientific-grade monitors, while the CO_2 sensor showed poor accuracy at high concentrations. The Car Canary prototype effectively alerted VO when $PM_{2.5}$ exceeded 50 µg/m^3, prompting RVCA activation to limit exposure.

The quality of the data was considered when interpreting these results. For $PM_{2.5}$, the home-made device correlated strongly with the research-grade monitor (Multiple $R = 0.89$; $R^2 = 0.80$), suggesting the $PM_{2.5}$ measurements were reasonably accurate, although the device consistently read lower than the research-grade monitor, which was corrected using a line of best fit. In contrast, the CO_2 sensor correlated poorly with the research-grade monitor (Multiple $R = 0.31$; $R^2 = 0.10$), so the CO_2 concentrations from the home-made device should be treated with caution and were not used in the final device. Precision and reliability were also limited by the small number of replicates (between three and seven per test) and by the use of a single vehicle with two occupants, which restricts how far the findings can be generalised. These results are broadly consistent with previous studies reporting elevated TRAP for vehicle occupants in road tunnels (Knibbs et al., 2009; Martin et al., 2016; Morawska et al., 2008) and with reports that recirculating cabin air can reduce particle exposure while affecting CO_2 concentrations (Jung et al., 2017; Kumar et al., 2021).

The limitations of this research include: limited TRAP parameters being measured due to time and material constraints and specific controls used that may not apply to all cars (e.g., vehicles with

more or less than 2 passengers). This study used the WestConnex M4–M8 tunnel system. The application of these results to other tunnel systems were not assessed.

Enhancements to the device could include monitoring multiple TRAP parameters and automating RVCA control for optimal air quality management. The study could be strengthened by including more replicates across varied vehicle types and routes, and by testing higher occupancy levels, which would directly increase CO_2 accumulation.

This study highlights the need for improved sensor accuracy and expanded TRAP monitoring to refine strategies for minimizing VO exposure to air pollutants and CO_2 in tunnels, however the findings provide valuable preliminary information and proof of concept.

CONCLUSION

Exposure to TRAP in tunnels poses a health risk to VO. This study reports TRAP and CO_2 concentrations being higher inside the WestConnex M4–M8 tunnel system, highlighting the need for targeted interventions. Air quality varied by treatment, with RVCA offering the most protection from TRAP but leading to CO_2 buildup. CO_2 levels exceeded 800 ppm in 3 minutes, 1000 ppm in 4 minutes, and 3000 ppm in 16 minutes. CO_2 at these levels has been associated with risks to cognitive function, fatigue, and infection transmission. While RVCA is the recommended mitigation strategy, this preliminary study suggests that prolonged use may increase exposure to CO_2.

To further reduce TRAP exposure, the study introduced Car Canary, a prototype device that alerts VO when TRAP reaches a critical level, signaling when to enable RVCA. This research provides valuable preliminary evidence and proof of concept, filling a gap by developing a device to balance TRAP and CO_2 exposure risks, with the aim of enhancing driver health and safety.

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