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Impact of Pressure Release Valves on Infiltration in Internal Combustion Engine Vehicles

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ABSTRACT: This study examined how the influence of the pressure release valve (PRV), a standard internal combustion engine vehicle (ICEV) component, affects ultrafine particle (UFP) concentrations inside the cabin. The goal was to understand how outside air and UFP enter vehicles and explore ways to reduce passenger exposure. It was hypothesized that the PRV contributes to infiltration and that reducing infiltration by controlling the PRV is feasible. On-road cabin and outside UFP concentrations and pressures were measured for one ICEV. The PRV was identified as the primary contributor to infiltration, as sealing it reduced cabin UFP concentration by 67% under air conditioning (AC) on and by 52% under AC off. Vehicle outside pressure near the PRV was higher than cabin pressure, supporting the occurrence of infiltration at the PRV. Differential pressures and fluid dynamics equations revealed that the PRV contributes approximately 87.5% of the ICEV's total infiltration area. Opening a calculated portion of the PRV can maintain a positive cabin pressure of 60 Pa. These findings demonstrated the potential to reduce cabin UFP concentration in ICEVs by controlling the PRV and creating positive cabin pressure. This approach offers a promising solution to enhance the UFP-reduction technology in ICEVs.

KEYWORDS: Environmental, Pollution Control, Pressure Release Valve, Ultrafine Particle, Infiltration.

Introduction

A pressure release valve (PRV) is an essential design component found in almost all passenger vehicles. Located near the rear bumper, the PRV is designed to relieve excess cabin pressure by opening lightweight flaps under door-closing or heating, ventilation, and air conditioning (HVAC) events.[1] While advanced mitigation strategies such as high-efficiency particulate air (HEPA) filters and positive-pressure environments have been shown to reduce in-cabin ultrafine particle (UFP) exposure in certain battery-electric vehicles (BEVs), other BEVs and most internal combustion engine vehicles (ICEVs) lack comparable technology.[2] The key limit may be caused by the PRVs in these vehicles. Although essential for passenger comfort, the large openings of PRV may also act as unintended infiltration pathways for UFP, especially when road vibrations or uneven surfaces cause the flaps to open.

Despite the prevalence of PRVs in some BEVs and nearly all ICEVs, their role in particle infiltration and their influence on cabin pressure regulation have not been systematically studied. This gap is significant given that over 90% of vehicles on U.S. roads remain ICEVs. Thus, most passengers continue to be exposed without access to positive-pressure technologies that are available in certain battery-electric models.[3]

To address the gap, this study investigated whether PRVs represent a major source of UFP infiltration and whether controlling their openings could enable the creation of a positive cabin pressure environment in ICEVs. The study combined on-road measurements of UFP concentrations and cabin pressure with a fluid dynamics analysis under both standard and PRV-sealed conditions. Results demonstrated that sealing the PRV reduced the in-cabin/outside UFP ratio (I/O) by 67% with air conditioning (AC) on and 52% with AC off, confirming its substantial contribution to infiltration. Pressure differentials measured across the vehicle cabin and outside, and ventilation flows further indicated that the PRV accounts for approximately 87.5% of the cumulative infiltration area in the tested vehicle. By strategically controlling PRV operation, it is possible to sustain a positive cabin pressure of 60 Pa, thereby reducing UFP ingress. These findings identify the PRV as a critical infiltration pathway in ICEVs and introduce a practical approach toward achieving positive cabin pressure without requiring major design overhauls. Such strategies may significantly reduce cabin UFP exposure for the vast majority of road users and inform future vehicle design improvements.

Methods

All measurements were conducted on the Mercedes-Benz ML350 (model year 2015), which was the ICEV used in this study. The vehicle was serviced in June 2024, and a new cabin filter was installed prior to the start of on-road testing. The vehicle was in good condition, with proper sealing at the doors, windows, trunk, and other potential locations of outside air ingress.

1.1. Measuring UFP Concentrations:

All UFP concentrations were measured using two Testo DiSCmini devices placed inside the Mercedes-Benz while driving. To sample outside UFP concentrations, the sampling tube passes through a thick neoprene sheet that fills the gap of a rolled-down window. The difference of the UFP concentration from the two DiSCmini devices is approximately 10%

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hence the directly measured UFP data are used for analysis. Additional details are described in the reference.[2]

UFP concentrations and I/O ratio were conducted under two conditions: with the PRV sealed (Tape On) and unsealed (Tape Off) in the ICEV. UFP data for Tape Off were reported in the reference and are used in this study as a baseline for comparison.[2] To tape the PRV, heavy-duty duct tape was used to seal the opening area of the PRV completely (access PRV from trunk side), limiting airflow into the cabin through the PRV. Numerous precautions were taken to ensure a well-sealed PRV, such as applying multiple duct-tape layers and complete coverage of the PRV opening area to mitigate the potential leaks. To comprehensively assess the influence of the PRV under different ventilation settings, four conditions were tested: Tape On, AC On; Tape On, AC Off; Tape Off, AC On; Tape Off, AC Off. Here, AC On indicates that the air conditioning system was activated to control air temperature, and the recirculation was turned off, while AC Off means all ventilation systems, including the air conditioning system and ventilation fan, were deactivated. Under the AC On mode, outside air was drawn into the cabin by the ventilation fan.

For measuring UFP concentration immediately outside the PRV (PRV Outside), one Testo DiSCmini device was put in the back of the vehicle cabin. One end of the vinyl sampling tube was routed through the PRV, extending approximately 1 inch beyond it to sample the UFP concentrations in the immediate external environment of the PRV. PRV outside is defined as the region between the frame and rear bumper of the vehicle, while vehicle outside is defined as the environment outside of the rear bumper. To extensively analyze UFP concentration at PRV outside, four conditions were tested: air conditioning on with recirculation off (AC On), all ventilation systems turned off (AC Off), air conditioning on with recirculation on (AC On Rec On), and ventilation fan on with air conditioning off and recirculation off (AC Off Fan On). Under the AC Off Fan On mode, outside air was drawn into the cabin by the ventilation fan.

The UFP I/O ratio was calculated as the ratio of the averaged cabin (inside) UFP concentration to the averaged vehicle outside UFP concentration for each test and is expressed as a percentage in this study. The overall UFP I/O ratio for a ventilation setting is the average UFP I/O ratio from 4 to 5 repeated tests under the same conditions.

1.2. Measuring Differential Pressure:

Differential pressures at various areas of the ICEV were obtained using a Machenhlic Micro Pressure Gauge with a measurement range of -500 to 500 Pa and a reading resolution of 20 Pa. To sample cabin pressure, an EZ-FLO 1/4" ID (3/8") PVC clear vinyl tube was connected to the negative port of the gauge, and the other end of the vinyl tube was placed inside the vehicle. To sample outside pressure, a second piece of clear vinyl tubing was attached to the positive port of the gauge. The opposite end of this tube was routed through a 3/8" hole in the thick neoprene sheet, which extended out of the vehicle and reached the desired exterior surface sampling location. To specifically measure static pressure, the exterior vinyl tube was secured to the vehicle's exterior surface using heavy-duty duct tape. The inlet of the vinyl tube was aligned parallel to the vehicle exterior surface and positioned to face away from the airflow direction, minimizing disturbances from the outside air movement. For convenience, the Machenhlic Micro Pressure Gauge will always measure static pressure and report differential pressures as the difference between outside and inside pressure ($Pressure_{outside}$ - $Pressure_{inside}$). Due to bumps in the road causing vibration while driving, the pressure readings on the pressure gauge varied in a range, so the middle value was taken. All fan speeds (Fan Speed 0–7) inside the Mercedes-Benz were measured with a hand-held anemometer while it was parked, both with a sealed PRV (Tape On) and an unsealed PRV (Tape Off) during AC Off conditions. The anemometer measures wind speed in meters per second.

1.3. Calculating PRV and Infiltration Areas:

The flow and pressure conditions inside the ICEV cabin were demonstrated using a simplified system with a flow rate from the fan (Q_{in}, m^3/s), a flow rate out of the vehicle (Q_o, m^3/s), the equivalent open area where cabin air exchanges directly with outside air (A, m^2), and the differential pressure (ΔP, Pa), as shown in the schematic diagram (Figure 1).

The fan flow rate, Q_{in}, is defined as u_i x A_{in}, where u_i is the air/wind speed at the fan exit (m/s) and A_{in} is the total area of the fan outlets (m^2). Fan speeds (m/s) were measured across fan speed settings 0–7 (u_i). The total fan outlet area was 0.0232 m^2, calculated from the measured dimensions of the fan outlets. Hence, the fan flow rate, Q_{in}, was 0.0232 x u_i. The amount of air that flows into the cabin is equal to the amount of air that flows out when maintaining constant pressure ΔP, so $Q_{in} = Q_o$.

The flow rate of cabin air leaking out due to a positive pressure can be calculated using Equation 1, which is derived from Bernoulli's equation, considering energy loss as static pressure is converted to dynamic pressure.[4] The flow rate of air leaking out of the cabin (m^3/s), Q_o, is represented as,

$$Q_o = C * A * \sqrt{2 * \Delta P / \rho} \qquad \text{(Equation 1)}$$

Where C is the discharge coefficient. In this study, we used the average value of 0.7 based on the range of 0.6–0.8.[4] A is the total area of openings in the cabin (m^2). Openings are defined as locations where air can escape from the cabin into the external environment. Since *A* represents the equivalent total area in the ICEV cabin that facilitates direct air exchange between the cabin and outside, it includes contributions from both the PRV and any cracks or holes in the vehicle. Their combined contribution is represented as $A_{infiltration}$. The area of the PRV is denoted as A_{PRV}, and $A = A_{PRV} + A_{infiltration}$. A_{PRV} was calculated to be 0.0412 m^2 based on the measured dimensions of the two PRVs in the ICEV; ΔP is the differential pressure between the cabin and the outside (Pa) where a positive value indicates higher pressure inside the cabin than outside the vehicle; and ρ is the density of air (kg/m^3), taken as 1.204 kg/m^3 (air density at 20 °C).

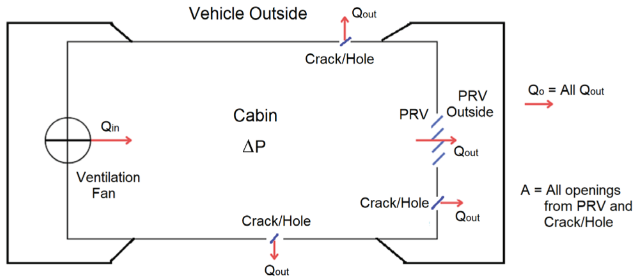

Figure 1: Simplified system of Mercedes-Benz cabin environment. The diagram shows flows, pressure, and opening areas of the cabin environment.

1.4. On-Road Testing Route:

All on-road tests were conducted on the I-10, I-71, and I-60 freeways in Los Angeles, California. Each on-road test typically lasted between 30-60 minutes. Additional details are described in the reference.[2]

Results and Discussion

2.1. PRV Outside UFP and Its Influence on Cabin UFP:

The PRVs were hypothesized to be a major source of infiltration in the ICEV. To evaluate whether outside air with high UFP concentrations can enter the area near the PRV, UFP concentrations at the PRV's outside, located between the PRV exterior and rear bumper interior, were measured and compared to the vehicle's outside UFP concentrations during on-road driving of the Mercedes-Benz. The test was conducted under four commonly used conditions: AC On, AC Off, AC On Rec On, and AC Off Fan On.

For the majority of the approximately 60-minute sampling period along the test route using the Testo DiSCmini, the PRVs' outside UFP concentration closely mirrored the vehicle's outside UFP concentration, following similar changes and patterns. The PRV outside UFP concentration was approximately 66% to 73% of the vehicle's outside UFP concentration (Figure 2). When the vehicle's outside UFP concentration peaked at 4.9x10^5 particles/cm^3, the PRV outside UFP concentration peaked at 3.9x10^5 particles/cm^3.

The PRV outside can potentially experience high UFP concentrations, measuring about two-thirds of the vehicle's outside UFP concentrations. However, during the period from 8:16 to 8:24 under the AC Off Fan On condition, the PRV outside UFP concentration did not follow the vehicle's outside UFP concentration. In this mode, the fan blows outside air into the cabin, forcing cleaner cabin air to exit through openings such as the PRV in the vehicle frame. Previously, between 8:08 and 8:15, the Mercedes-Benz operated under AC On with Recirculation On, which resulted in lower cabin UFP concentration due to continuous filtration. When the mode switched to the AC Off Fan On condition, the fan introduced unfiltered outside air into the cabin and pushed the continuously filtered cabin air out through the PRV, which was sampled by the vinyl tube that measured PRV outside UFP concentration. Despite this discrepancy, the PRV exterior UFP concentration still tracked the vehicle's outside UFP concentration during most of the sampling period. This observation suggests that outside air frequently enters the area around the PRV. Since the PRV is essentially a large opening in the vehicle that allows direct interaction between external and cabin air, it represents a potential major infiltration point in ICEVs such as the Mercedes-Benz in this study.

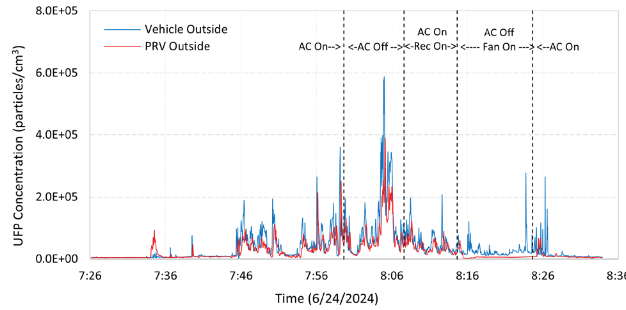

Figure 2: PRV Outside and Vehicle Outside UFP concentrations comparison. PRV outside UFP concentrations closely follow vehicle outside UFP concentrations, reaching approximately two-thirds of their levels under different vehicle ventilation conditions.

To further investigate the influence of the PRV on infiltration and cabin UFP concentrations while an ICEV was on-road, multiple tests with the Mercedes-Benz were conducted under four conditions to compare UFP I/O ratios: Tape On AC On, Tape On AC Off, Tape Off AC On, and Tape Off AC Off. A lower I/O ratio represents better effectiveness in reducing cabin UFP concentrations.

Sealing the PRVs in the ICEV significantly reduced UFP I/O ratios (Table 1). Under the Tape On AC On condition, the I/O ratios were in the range between 3.6% and 13.7%. This represents a drastic decrease compared to the Tape Off AC On condition, where all tests yielded an overall average I/O ratio of 19.9% (Table 1). Similarly, I/O ratios measured in Tape On AC Off ranged from 5.1% to 20.4%, significantly lower than the overall average I/O ratios of 30.8% (Table 1). Overall, for AC On, the average I/O ratio decreased from 19.9% with Tape Off to 6.6% On, a 67% decrease. For AC Off, the average I/O ratio decreased from 30.8% with Tape Off to 13.8% On, a 55% decrease. Since an over 50% decrease in cabin UFP concentrations by sealing the PRV was observed, the PRV was deemed a major infiltration source.

UFP I/O ratios when the PRVs were sealed were significantly lower than those for unsealed PRVs, both when the AC was on and when it was off. When the PRV was completely sealed, potential infiltration through the PRV openings was eliminated. With the PRV sealed, ventilation air blown in by the fan under AC On conditions cannot escape through the PRV, instead exiting through the designated AC flow pathways, cracks, or other small openings in the vehicle. Sealing the PRV may effectively block infiltration points and reduce cabin UFP concentrations. Under the AC On condition, the cabin pressure was observed to be equal to the vehicle's outside pressure when the vehicle was stationary and parked, regardless of whether the PRVs were sealed. This indicates that sealing the PRVs did not change the ventilation flow rate under the AC On mode. Therefore, the contribution of UFP from ventilation air to cabin UFP should be similar under PRV sealed and unsealed conditions. Similarly, under Tape On AC Off

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conditions, unfiltered outside air can no longer enter the vehicle through the PRV, reducing infiltration and lowering inside UFP concentrations. This phenomenon explains the behavior of infiltration when the PRV is sealed and the major reductions in I/O ratios of 67% for AC On and 55% for AC Off. These findings indicate that the PRV is a primary infiltration pathway for outside air with high UFP concentrations to enter the cabin, thereby supporting the first part of the hypothesis.

The overall UFP I/O ratio for AC On (6.6%) and AC Off (13.8%) with a taped PRV (Tape On) in this study was lower than those reported in previous research, which ranged from 20% to 110%.[5,6] These findings highlight that controlling the PRV has the potential to reduce passenger exposure to UFP substantially.

Table 1: Mercedes-Benz UFP measurements for Tape On AC On, Tape On AC Off, Tape Off AC On, and Tape Off AC Off. UFP I/O ratios decreased substantially under the Tape On condition (PRVs sealed) compared to the Tape Off condition (PRVs in normal state), indicating the PRVs are a major infiltration pathway.

	Date	Mean Inside UFP (particles/cm^3)	Mean Outside UFP (particles/cm^3)	Mean I/O Ratio	Overall I/O Ratio
Tape On	6/23/2024	767	15,489	5.00%	6.6±4.8%
	7/11/2024	2,878	21,081	13.70%	
	9/17/2024	3,394	84,540	4.00%	
	9/20/2024	2,859	79,101	3.60%	
Tape On	6/23/2024	1,090	21,300	5.10%	13.8±5.5%
	7/12/2024	7,427	51,856	14.30%	
	9/17/2024	10,446	51,139	20.40%	
	9/20/2024	8,288	57,540	14.40%	
	9/21/2024	10,975	75,067	14.60%	
Tape Off	*Overall I/O Ratio AC On: 19.9±4.6%* *Overall I/O Ratio AC Off: 30.8±10.2* *Overall I/O ratio data for Tape Off are retrieved from the reference, where the same Mercedes Benz vehicle was tested.*[1]				

Under Tape Off conditions, the I/O ratio for AC On (19.9%) was lower than that for AC Off (30.8%) (Table 1). Under AC On mode in this study, the vehicle was operated with outside air being continuously drawn by the fan and entering the cabin while the recirculation was turned off. This difference is likely due to the high-efficiency cabin filter and the air conditioning system of the Mercedes-Benz, which partially removes UFP from outside air as it is drawn into the cabin. Under the AC Off condition, although a small amount of outside air may be driven by the dynamic pressure at the vehicle front and enters the cabin, no air is actively blown into the cabin by the ventilation fan, leaving all infiltration locations unblocked. As a result, unfiltered outside air with potentially high UFP concentrations can enter the cabin through openings such as the PRV. Depending on the vehicle design, a similar trend is observed under Tape On conditions, where the I/O ratio for AC On (6.6%) is lower than AC Off (13.8%). Notably, the UFP I/O ratio of 13.8% under Tape On AC Off is even lower than the I/O ratio of 19.9% observed under Tape Off AC On, further underscoring the PRV's major contribution to infiltration.

UFP concentrations in this study were estimated using Testo DiSCmini, which detects particle sizes ranging from 10 to 300 nanometers. UFPs, defined as aerodynamic sizes less than 100 nanometers, are dominant in the airborne particle size distribution.[7,8] The reported UFP concentration in this study may be approximately 10% higher than the true UFP concentration; however, this influence on the UFP I/O ratio is expected to be ignorable. Also, sealing the PRV using duct tape can cause small leaks and may not completely represent a fully sealed PRV. If the PRV were to be sealed but leaks still occurred, the reduction in the I/O ratio observed would be lower than the ideal sealed PRV condition. Thus, a more I/O ratio reduction with a completely sealed PRV is expected.

2.2. Vehicle Outside Pressure near PRV:

To identify infiltration locations in the vehicle frame and determine a target value for positive cabin pressure, differential pressures (DP) were measured at various locations. DP was calculated as $Pressure_{outside}$ - $Pressure_{inside}$. A positive DP indicates that outside pressure was higher than cabin pressure (referred to as negative cabin pressure). In comparison, a negative DP signifies higher cabin pressure than outside pressure (referred to as positive cabin pressure).

In this study, the DP for the window under Tape Off steadily decreased as vehicle speed increased, indicating that cabin pressure became progressively greater than the outside pressure (Figure 3). The DP decrease was steeper in the Tape On case, demonstrating a more pronounced DP reduction as vehicle speed increased. For the trunk area, the DP for Tape Off increased with vehicle speed and remained positive, peaking at 50 Pa at 70 mph (Figure 3). Conversely, under Tape On, the DP remained negative at high speeds and peaked at -50 Pa at 70 mph (Figure 3). The DP near the trunk area illustrated contrasting trends: a DP increase for Tape Off and a DP decrease for Tape On. These measurements highlight how sealing the PRV impacts DP across different vehicle locations.

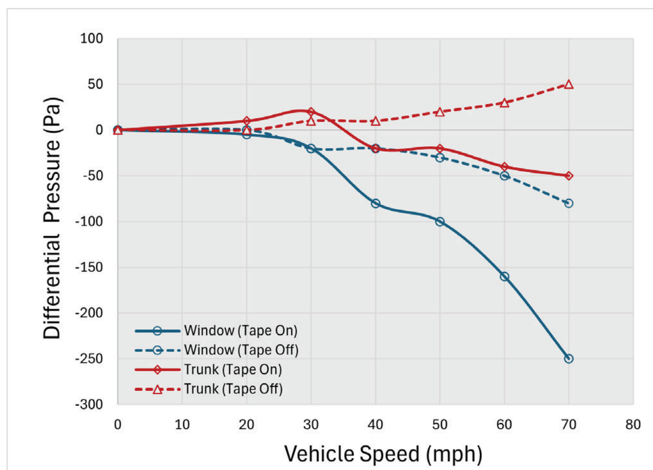

Figure 3: Differential pressures at the window and trunk during on-road driving. "Tape On" means the PRV was sealed with duct tape, and "Tape Off" means the PRV was open and not sealed. Under the Tape Off condition, positive differential pressures were observed near the trunk area, indicating higher vehicle outside pressure relative to cabin pressure. As the PRVs are located near the trunk, this pressure gradient may drive outside air through the PRVs into the cabin.

It was observed that DP changed with vehicle speed, exhibiting distinct trends at different locations (Figure 3). At the Mercedes-Benz window, the decrease in outside pressure is attributed to increased vehicle speed that induces greater air movement and raises outside dynamic pressure. The more pronounced decrease in DP by the window when the PRV was sealed likely resulted from an increase in cabin pressure. This occurs because a sealed PRV reduces the total area available for releasing pressure buildup within the cabin. Our tests revealed that the rear bumper consistently experiences higher pressure than the cabin, even when the PRV was sealed. Overall, our DP findings align with findings from simulations, which indicate that the front and rear of the vehicle are subject to outside pressures that are higher than cabin pressures, whereas the sides and roof of the vehicle experience lower outside pressure than cabin pressure.[9] On-road tests further confirmed this behavior, showing similar DP trends at the rear bumper and side windows.[10] These observations suggest that the front and back of ICEVs are major infiltration locations for UFPs. In contrast, the sides of ICEVs are less susceptible to infiltration when the vehicle is on-road. These observations further support our hypothesis that the PRV contributes to major infiltration in ICEVs, given that the PRV's location is in the rear of the vehicle.

In this study, the DP reported for the Mercedes-Benz is measured as a static pressure. While on-road, the instantaneous DP may fluctuate randomly and uncontrollably for each location due to factors such as passing vehicles or wind, which can induce additional dynamic pressure.[11] As a result, the outside pressure may occasionally exceed the measured values, altering the reported DP. For locations where DP is positive, real-world effects such as vehicles passing by and wind may cause the DP to be more positive. Conversely, if the DP is negative, these effects could make the DP less negative or even positive. Since these fluctuations are uncontrollable and occur only sporadically, they are not accounted for in calculations evaluating the feasibility of creating a positive-pressure environment by controlling the PRV.

2.3. Estimate Opening Areas on Vehicle:

The UFP measurements have demonstrated that sealing the PRV reduced the UFP I/O ratio by over 50% in the Mercedes-Benz vehicle. To better understand the mechanism behind the major influence of the PRV on infiltration and the cabin UFP I/O ratio, cabin pressures and airflow are analyzed to examine infiltration through the PRV and other locations.

While the vehicle was stationary and under AC Off Fan On (the air conditioning was turned off, the ventilation fan was turned on, and recirculation was turned off), DP under Tape On became increasingly negative (indicating the cabin pressure was progressively higher than the outside pressure) and peaked at -485 Pa at Fan Speed 7. In contrast, when the PRV was unsealed and operating normally, the DP remained at nearly 0 across all fan speeds (Figure 4). The cabin pressure did not increase when outside air flowed into the cabin, which may be attributed to the large opening area of the PRVs specific to this tested vehicle. Additional vehicles with different designs and PRV sizes will be evaluated in future studies.

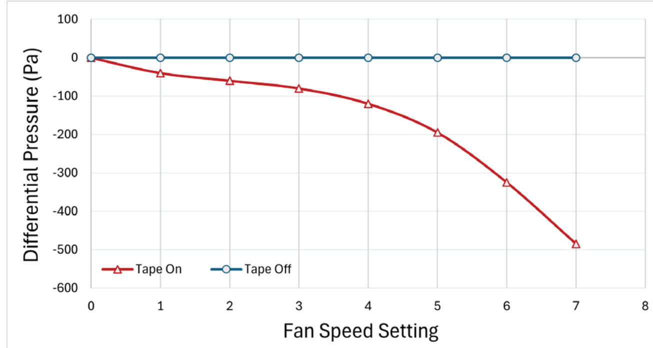

Figure 4: Differential pressures for different fan speed settings and PRV settings while idle. "Tape On" means the PRV was sealed with duct tape, and "Tape Off" means the PRV was open and not sealed. The DP reading was stable in this experiment because the vehicle was idle and parked while both Tape On and Tape Off conditions were tested. Positive cabin pressure can be established under the Tape On condition, but not under the Tape Off condition, indicating PRVs hinder the creation of positive cabin pressure.

Next, the infiltration area was estimated based on the measured pressure differences ΔP ($Pressure_{inside}$ – $Pressure_{outside}$) with the PRV taped, the measured ventilation airflow exiting the fan, the measured PRV opening area (0.0412 m^2), and a derivation of Bernoulli's fluid dynamics equation incorporating the discharge coefficient. With the PRV sealed, the opening area of the PRV is 0 ($A_{PRV} = 0$), and only holes and cracks contribute to the total infiltration area. Additionally, the airflow into the cabin from the fan is equal to the amount of air exiting through these holes and cracks to maintain a stable ΔP at each fan setting. In our experiment, the highest fan speed (Fan Speed 7) achieved a velocity of 5.2 m/s and a flow rate of 0.123 m^3/s through a fan exit area of 0.0232 m^2. The total infiltration area of the Mercedes-Benz with a sealed PRV was estimated to be 0.0059 m^2, which is about six times smaller than the infiltration area created by the PRV when it is open (Figure 5).

The manual measurements of A_{PRV} (0.0412 m^2) and the estimated $A_{infiltration}$ (0.0059 m^2) using ΔP measurements and Bernoulli's fluid dynamics equation (Equation 1) indicated that the PRV was nearly 6 times larger than the total area of cracks and holes in this specific vehicle. The large area of the PRV suggests that, when PRVs are not sealed, they can potentially become the primary infiltration source due to their much larger opening area. The substantial difference between the PRV area (0.0412 m^2) and the cracks/holes area (0.0059 m^2) suggests that the large PRV opening likely facilitates considerable infiltration, further validating the first part of the hypothesis (Figure 5). While estimating $A_{infiltration}$, the value of 0.7 is chosen for the discharge coefficient using the middle value of its range of 0.6 to 0.8.[4] This was motivated by the fact that airflow conditions are complex due to the irregular geometry of the vehicle, cabin, and scattered locations of cracks/holes. If we chose the discharge coefficient to be 0.6 (lower bound) or 0.8 (upper bound), the calculated $A_{infiltration}$ would increase by 17% or decrease by 13%, respectively, making the A_{PRV} still magnitudes greater than $A_{infiltration}$. The assumption of constant air density at 20 °C has a negligible effect on the

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estimation. When the air temperature increases to 25 ˚C, the estimated area decreases by approximately 0.8%.

2.4. Controlling PRV Opening to Build Positive Cabin Pressure:

Sealing the PRV greatly reduced the UFP concentration inside the cabin (Table 1). It can also establish positive cabin pressure in the Mercedes-Benz vehicle, as demonstrated earlier (Figure 4). Therefore, controlling the PRV opening has the potential to create and maintain a desired positive-pressure environment, thereby mitigating infiltration. Airflows were analyzed using Bernoulli's fluid dynamics equation, along with the area of the PRV and cracks/holes, to create a positive cabin pressure environment by adjusting the opening area of the two PRVs in the Mercedes-Benz at different fan settings during AC off conditions.

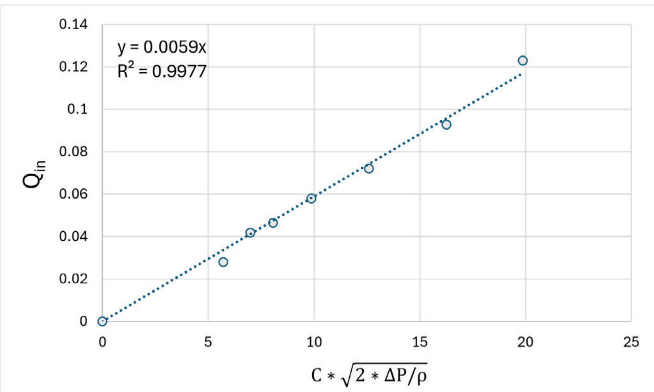

Figure 5: Measurements to obtain the area for the uncontrolled cracks/holes in the Mercedes-Benz. The regression analysis estimated an effective cracks/holes area of 0.0059 m^2, which is substantially smaller than the measured PRVs area of 0.0412 m^2.

Given that the outside pressure peaked at 50 Pa higher than the cabin pressure during the DP measurement, a desired ΔP of 60 Pa was set to ensure that the cabin pressure remains marginally higher than the outside pressure in most situations. By adjusting the PRV opening area, the Mercedes-Benz cabin pressure can be controlled to achieve ΔP of 60 Pa. At higher fan speeds, which increase the amount of ventilation air entering the cabin, a larger PRV opening area is required to maintain the same cabin pressure (Table 2). At the highest fan speed (Fan speed 7), each PRV needs to open 28.37% to sustain a ΔP of 60 Pa during AC Off Fan On conditions (Table 2). The positive and feasible percentages of PRV opening (PCT) and adjusted PRV areas (A_{PRV}) support the second part of our hypothesis: controlling the PRV can effectively create a desired positive cabin pressure in ICEVs.

Minor discrepancies, such as a non-zero percentage of PCT under Fan Speed 2, arose from rounding errors during the calculation of infiltration areas from cracks and holes; however, these errors of 0.20% are minimal. The calculated PRV opening area ($A_{PRV\text{-}open}$) and opening percentage are specific to this Mercedes-Benz. Other manufacturers can adopt a similar methodology to estimate these parameters for their vehicles similarly and feasibly. Controlling the PRV opening by purely blocking or reducing the PRV opening area may compromise the PRV's original function of releasing cabin pressure during door closure quickly. Using electronic equipment to control PRV opening may increase system complexity and demand stable operation. Also, reducing the PRV opening area may reduce the infiltration flow through the PRV into the cabin, resulting in a lower air exchange rate and potential increase in cabin CO_2 levels, an effect to be further investigated in future studies. To control the PRV opening, it is suggested that manufacturers opt for a mechanical strategy to ensure the PRV is consistently able to open and release pressure during door closure, but also able to change its opening area to build a desired positive cabin pressure during driving. For AC On conditions, controlling the PRV opening area must account for the AC air exit route. This exit route may hinder the creation of positive cabin pressure, as cabin air may also flow out through the AC exit area – a factor not addressed in this study.

Conclusion

In summary, the PRV contributes major infiltration as indicated by the fact that sealing the PRV reduced the UFP I/O ratio by over 50% for both AC On and AC Off cases. High UFP concentrations in the immediate external vicinity of the PRV and higher outside pressure than cabin pressure were found near its location. This study also discovered that PRVs account for approximately 87.5% of the area of vehicle openings to the outside environment and hinder the creation of a positive cabin pressure for the ICEVs. Still, its opening can be controlled to maintain a desired positive cabin pressure.

Table 2: Total area and percent area that the two pressure release valves (PRVs) in the Mercedes-Benz need to open to maintain a differential pressure of 60 Pa. $A_{PRV\text{-}open}$, the opening area of the PRV, is calculated by A-0.0059. PCT, the percentage of PRV needs to open, is calculated by its corresponding $A_{PRV\text{-}open}$ /0.0412*100. "/" represents that a fan speed setting cannot build a positive cabin pressure of 60 Pa for the Mercedes-Benz. The results on the PRVs' opening percentages indicate that creating positive cabin pressure through PRV control is feasible.

Fan Speed Setting	Fan Speed (m/s)	$A_{PRV\text{-}open}$ (m^2)	PCT
0	0.0	/	/
1	1.2	/	/
2	1.8	0.0001	0.20%
3	2.0	0.0007	1.81%
4	2.5	0.0024	5.83%
5	3.1	0.0044	10.66%
6	4.0	0.0074	17.91%
7	5.3	0.0117	28.37%

The data supported that the PRV is the major source of infiltration for ICEVs and that controlling the PRV opening can create a desired positive cabin pressure to reduce infiltration. These revealed a potential solution for controlling the PRV openings to reduce cabin UFP concentrations in ICEVs significantly. Nevertheless, these conclusions are based on only one ICEV used in this study. Different vehicle models, makes, ages, and operation methods may have variations in PRV sizes, ventilation flows, as well as in the number and size of cracks/holes that allow outside air to enter the vehicle cabin. Higher ventilation flows are generally required to achieve a desired positive cabin pressure in vehicles with larger total infiltration areas, such as older or not well-maintained vehicles with bigger gaps around doors and windows, or vehicles equipped with larger PRVs, and vice versa. As such, different types and operating conditions of vehicles may need to use different ventilation fan flows to build the positive cabin pressures necessary to prevent infiltration, a factor to be considered during the design phase of implementing this method. This variation in PRV opening area will not affect the fact that it is a primary infiltration pathway, as the PRV area was discovered to be greater than the area of cracks/holes. Further studies will expand on these findings by testing more ICEV models, as well as by considering both AC Off and AC On conditions to design, develop, and test a cost-effective PRV-controlling system capable of mitigating cabin UFP concentrations in ICEVs for all ventilation conditions. Overall, the successful mitigation of cabin UFP in ICEV could potentially have a meaningful impact on reducing the UFP exposure, as it may ultimately protect the health of millions of people while driving on roadways where high outside UFP levels exist.

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