Carpark mechanical ventilation – time to take performance seriously?

Craig Pregnalato, PhD, BEng(Hons), M.AIRAH – Director at Desanco

ABSTRACT

Recent adoption of the 2019 National Construction Code (NCC) has highlighted the improvements attainable in energy efficiency and sustainable design. However, the same cannot be said of the antiquated ventilation requirements for carparks in Section F of the NCC. The Deemed-to-Satisfy (DtS) provisions of the NCC state that carpark ventilation systems should comply with AS1668.2, yet the vehicle emission rates (and the corresponding exhaust ventilation flow rates) in AS1668.2 have not changed in almost 20 years. This despite the fact that automobile technology has made huge advancements considering increasingly stringent exhaust emission requirements – modern vehicle fleets have transitioned to smaller more efficient engines, and the progressively larger market-share of electric and hybrid vehicles. It is therefore timely to consider how Performance Solutions for carparks can lead to better designs that are more reflective of modern energy-efficient and sustainable policies.

INTRODUCTION

Compliance with the NCC[1] for carpark ventilation may be achieved via two pathways, namely the DtS approach or a Performance Solution. The performance requirements are detailed in FP4.3 and FP4.4 of the NCC, and the corresponding verification method is FV4.2 which states that carbon monoxide (CO) exposure levels should not exceed the limits specified in Table FV4.2 (reproduced here in Table 1).

The DtS provisions state that the carpark must have a system of mechanical ventilation complying with AS1668.2;[2] it is inferred that a ventilation system designed in accordance with AS1668.2 should result in CO levels in the carpark that are within the limits specified in Table 1. It is difficult to verify if this holds true in practice since DtS designs are hardly ever subject to performance appraisals; indeed, many DtS designs are often found to be non-compliant when assessed in comparison with Performance Solutions.

In light of this, it is suggested that Performance Solutions for carpark ventilation systems should be considered more seriously instead of defaulting to the DtS methodology – it is demonstrated that alternative considerations of the primary factors that amount to a DtS design have the potential for significant design improvements and cost advantages. Some of these parameters include:

- Using more representative vehicle emission rates;
- Considering actual vehicle speeds in carparks;
- Employing ambient background CO levels obtained from relevant Environmental Protection Agency data;
- Better estimating vehicle parking times or exit durations.

Concentration (ppm)	Total exposure duration per day
100	Not to be exceeded
90	15 minutes
60	1 hour
30	8 hours

Table 1. Maximum carbon monoxide exposure for carparks.

VEHICLE EMISSION RATES

The emission rate of CO from internal combustion engines is highly dependent on a number of factors, including the age of the vehicle, engine temperature, vehicle speed and ambient temperature, to name but a few. The CO emission rates are higher for older vehicles, when starting from cold, and for low ambient air temperatures.

When considering the emission rates for vehicles in carparks, it is important to separate the emission rates from "cold-start" (at initial start-up when the engine is cold, assuming a cold soak period of six-plus hours) and "hot running" (where the vehicle engine and emission control technologies have reached their optimal operating temperatures). At an ambient temperature of around 20°C, hot running conditions will generally be achieved within 15 minutes of driving; however, the magnitude of cold-start emissions is largely determined by "light-off" conditions of the catalyst and tight control of the air-to-fuel ratio. This is usually achieved within a minute of engine start for modern vehicles and a few minutes for older vehicles.[3]

A history of the vehicle emission rates in the current and previous versions of AS1668.2 is shown in Table 2. The vehicle emission rates in AS1668.2-1991 are based on 1990 fleet mix with 25% catalyst cars; the basis of the emission rates for the 2002 and 2012 versions are not described in the standard, however, the 2012 edition states that "emission controls do not start functioning effectively until several minutes after the engine has been in operation".[2]

It is important to note that since the emission rates in the current version (2012) of AS1668.2 *are independent of advancement in engine and emission control designs*, it follows that these values are inherently conservative and are not reflective of the emission rates that may be expected in current vehicle fleets, especially considering the trends towards smaller more efficient petrol and diesel engines, as well as the adoption of electric vehicles and hybrid technology.

In addition, these emission rates and the corresponding basis of the airflow rates in Appendix J of AS1668.2 are *informative*, and are therefore to be considered only for "information and guidance". It is disappointing to observe that in our experience, too many certifiers and building surveyors are unwilling to accept solutions that depart from these values or the ventilation airflow rates that follow. This can make acceptance of a Performance Solution a difficult value proposition for the proponent, and helps to explain why so few carparks are designed as a Performance Solution even though the benefits greatly outweigh those of a DtS design as discussed herein.

To alleviate these apparent concerns, a prospective Performance Solution should detail the vehicle emission rates used together with appropriate references. For cold-start emissions a good starting point is the study by Singer *et al.*[4], which details vehicle emission measurements in a three-level underground carpark. Pollutant concentrations and vehicle movements were measured during morning and afternoon sample periods; the median age of vehicles in this study was a manufacture year of 1991, with a larger proportion of cars in the range 1989–1997. Analysis of the data suggests emission rates typically two to three times lower than those in Table 2.

For hot engine emissions, one can consider the exhaust emission rates set out in the Australian Design Rules (ADR) for light vehicles as far back as 1976. Recent motor vehicle census data[5] shows that the average age of vehicles across Australia is 10.2 years as at January 2019, corresponding to an average manufacture year of 2008. The relevant ADR for these vehicles is ADR79/02, which references the Euro 4 test standard; the resultant emission standard for CO is 1.0g/km.[6]

To statistically allow for a wider range of vehicles, it may be suggested that the older ADR79/01 standard be applied with a CO emission standard of 2.3g/km; note that this emission standard is more stringent and covers vehicles (in terms of CO emissions) manufactured from 1997 onwards.

The intended use of the carpark also affects the choice of vehicle emission rates to use. For residential carparks, the peak hour for CO emissions could be in the morning when occupants depart for their workplaces; it is likely in this scenario that the vehicle engines would have had sufficient cold soak time (eight-plus hours) to have cooled completely such that cold-start emissions would be significant. Likewise, for commercial carparks, the peak hour could be in the afternoon when occupants depart on their home journeys. A vehicle cold soak time of eight hours would be a reasonable assumption in this situation.

On the other hand, for retail carparks, a peak hour for vehicle movements is more difficult to ascertain – if a traffic study is available for the development, then this may be used to estimate the distribution of vehicle movements over a given time period. In lieu of a traffic study, assumptions would need to be made regarding the duration of individual visits; vehicle cold soak times could range from as little as 15 minutes to a full day. The influence of the cold soak time on the CO emission rates would need to be considered as discussed in Favez *et al.*[7] Alternatively, cold-start conditions could be assumed which may result in excessively high CO emission rates.

Time	AS1668.2-1991	AS1668.2-2002	AS1668.2-2012
1st minute	35g/min	25g/min	25g/min
2nd minute	24g/min	16g/min	16g/min
3rd minute	17g/min	10g/min	10g/min
4th minute	13g/min	7g/min	7g/min
5th minute	10g/min	5g/min	5g/min
Hot	8g/min	3.2g/min	3.2g/min

Table 2. Vehicle CO emission rates in the current and previous versions of AS1668.2.

AVERAGE SPEED IN CARPARKS

In addition to the emission rates described above, AS1668.2 uses an average car speed of 6km/hr in calculating the CO contaminant generation rates. These rates consider vehicle movements when exiting the carpark, since the departing scenario is when the emission rates are highest because of cold engine starts.

Speed limits in carparks vary across the states, with most jurisdictions categorising carparks as Shared Zones, which generally attract a speed limit of 10km/hr. Where carparks can be classified separately a different speed limit can be applied; in Victoria for example, the VicRoads speed zone guidelines[8] state a 20km/hr speed limit for carparks and similar areas where vehicles and pedestrians mix.

A Victorian government inquiry into pedestrian safety in carparks[9] described a series of studies in Melbourne that investigated the actual vehicle speeds observed within regional and local shopping centre carparks. It found average speeds ranging from 14–30km/hr, with speeds of up to 60km/hr detected. The inquiry also recommended that carparks be designated Shared Zones where appropriate.

The study by Singer *et al.*[4] evaluated vehicle emissions and movements in a three-level underground carpark in 1997; the average vehicle speed measured was 16–24km/hr although the sign posted speed limit was 8km/hr.

It is reasonable to assume that vehicles entering carparks are likely to travel at lower speeds in their search for an available parking space; conversely, vehicles departing the carpark are more likely to travel at higher speeds as they make their way direct to the exit. Considering the above points, it may be advocated that a more representative departing vehicle speed used in a Performance Solution could be 15–20km/hr.

AMBIENT CO CONCENTRATION

In AS1668.2 [2] a peak ambient CO concentration of 9ppm is assumed; this is based on the National Environment Protection Measure (NEPM) 8-hour average standard of 9ppm. Every state and territory measures CO at a number of locations (except Tasmania and the Northern Territory, which are not required to monitor CO levels); annual reports on current air quality are published by the respective state environmental protection authorities.

A recent national air quality report was published in 2010,[10] representing the period 1999–2008. Over this period, the 95th and 50th percentile concentrations showed a gradual decline at all reported monitoring sites; indeed, at the end of this period, the 95th percentile CO concentration was less than 2ppm at every station monitored.

More recent data may be obtained from the relevant state authorities. In Victoria, statistics for 2018 [11] show that the maximum eight-hour CO reading recorded at any of the monitoring sites was 1.8ppm; the highest 95th and 50th percentile concentrations were 0.9ppm and 0.3ppm respectively. The (informative) Appendix N in AS1668.2 [2] declares "where data from the relevant EPA or from site monitoring indicates a consistently lower ambient value, then that value may be used in calculations." It is put forward that for the purposes of choosing an ambient CO concentration for a carpark ventilation Performance Solution, a value equivalent to the 95th percentile from the relevant EPA would be a practical estimate.

PARKING TIMES

The basis of the exhaust flow rates in AS1668.2 make two important assumptions on the exiting strategy of vehicles, namely:

- A car takes 0.5 to 1 minute to leave the zone; and
- Cars exiting from other areas are in the second minute of operation.

These guesses make no allowance for the size or complexity of the carpark, and importantly imply that the driving distances/speed have no influence on the time vehicles spend in the carpark; indeed, the formulae assume a maximum vehicle transit time of two minutes. Obviously the larger the carpark the more inaccurate this assumption becomes. Likewise, for small carparks where the exit times could be one minute or less, the formulae over-predict the CO generation rates.

An alternative is to calculate the parking/exit times based on the actual driving/bypass distances and average vehicle speed – this can be performed easily for any carpark (including with multiple levels) and yields a much more realistic estimation of the vehicle transit times. Using this approach, transit times of six-plus minutes can be obtained for large multi-level shopping centre carparks during a representative peak hour scenario.

INFLUENCE ON CARPARK CO EMISSION RATES

It is evident that the total CO emission rates are highly dependent on the chosen vehicle emission rates and the average speed of vehicles in the carpark; altering these two parameters can have a significant impact on the calculated CO emission rates.

To illustrate this, consider the carparks in Table 3, which represent a broad range in terms of size and usage. Here we have a small single-level residential carpark that is representative of a townhouse complex; a medium-size multi-level commercial carpark typical of an office block; and a large multi-level retail carpark that is characteristic of a shopping centre. All three examples presented are actual projects where Performance Solutions have been obtained.

For all three categories of carpark, the CO emission rates were computed using average driving and bypass distances (depending on the carpark layout) as referenced in AS1668.2. In addition, the parking times assumed in AS1668.2 (discussed above) were not used; instead, the vehicle transit times were calculated based on the actual driving/bypass distances and average vehicle speed. The CO emission rates were then calculated for every level and integrated to yield the total emission rates for each carpark. The influence of the vehicle emission rates and average vehicle speed assumed was assessed for the following scenarios:

- **Standard** – using the standard calculation procedure in AS1668.2 (Case 1);
- **High speed** – using an average vehicle speed of 10km/hr instead of 6km/hr. The term "high speed" is used here purely to distinguish from the "standard" speed of 6km/hr (Case 2);
- **Reduced** – using more representative emission rates,[4,6] (Case 3) and typically two to three times lower than the values in Table 2;
- **Reduced and high speed** – a combination of the above two scenarios (Case 4).

Table 3 and Table 4 show that the effects of altering these parameters can be significant, both in absolute and percentage terms. For the carparks considered here, just assuming an average vehicle departing speed of 10km/hr can reduce the calculated CO emission rates by almost 20%; if higher speeds can be justified, then the reductions will be more substantial.

Even more extensive are the reductions in calculated CO emission rates when more representative vehicle emission rates are used; here, reductions of approximately 70% are demonstrated. Since these emission rates directly affect the required exhaust flow rates, the corresponding reductions in exhaust flow rates are equally significant. In our experience, for small residential carparks where the simple procedure [2] is usually followed (typically yielding a minimum exhaust flowrate of 2,000L/s) the calculated flow rate reduction with a Performance Solution can be 80% or more. For larger commercial and retail carparks, exhaust flow rate reductions of 50% and greater are not unusual.

Size	Type	No. of levels	No. of cars	Total CO Emission Rates (g/hr)			
				Standard	High Speed	Reduced	Reduced and high speed
Small	Residential	1	31	174	151	80	69
Medium	Commercial	9	456	12,201	10,147	3,536	3,304
Large	Retail	3	1,011	41,006	33,990	11,578	10,744

Table 3. Comparison of total computed CO emission rates.

Size	Type	No. of levels	No. of cars	Total % Reduction from standard emission rates			
				Standard	High Speed	Reduced	Reduced and high speed
Small	Residential	1	31	n/a	13%	54%	60%
Medium	Commercial	9	456	n/a	17%	71%	73%
Large	Retail	3	1,011	n/a	17%	72%	74%

Table 4. Reduction in total CO emission rates.

EXAMPLE PERFORMANCE SOLUTION

We present now a real-world example showing how the ideas above can be implemented to positively impact the design outcomes.

A computational fluid dynamics (CFD) approach is adopted to assess the performance of the ventilation system as a Performance Solution. Since the airflow circulation in a carpark (and the corresponding dispersion of CO) is highly dependent on the distribution of obstacles and obstructions, it is imperative to include all significant impediments in the CFD model – these include vehicles, columns, ductwork and ceiling beams as a minimum.*

A one-level basement commercial carpark is considered here with a DtS exhaust flow rate of 7,700L/s, a supply flow rate of 6,200L/s and an ambient CO concentration of 9ppm; the CFD model geometry is shown in Figure 1. Supply air is provided via the carpark entry and ducted system on the south side; contaminated air is extracted via the exhaust system on the north side. Since attendant parking is not used, occupants will not be exposed to CO for long durations and therefore the eight-hour CO concentration limit of 30ppm (Table 1) is not applicable. Instead, the (correct) compliance criterion to use is the 1-hour average limit of 60ppm. It should be noted that different requirements including workplace health and safety may be applicable if attendant parking is employed.

The four scenarios mentioned above were simulated to appreciate the impact each change would have on the computed CO concentrations; the results are presented at an assessment plane 1.6m above floor level in Figure 2 up to a scale of 60ppm (i.e., the one-hour average criterion). Note that CO concentrations greater than 60ppm are not elucidated but are instead captured within the solid red contours. The spatial average and maximum CO concentrations (across the assessment plane) are summarised in Table 5.

It is interesting to note that the DtS design (Case 1) yields CO concentrations that are much higher than the 60ppm criterion in a large proportion of the carpark – this illustrates the fact that the one-size-fits-all DtS approach does not always result in a compliant ventilation layout, and serves as evidence that the well-intentioned performance requirements in the NCC are not necessarily satisfied by DtS designs.

By considering a higher average car speed in the carpark (Case 2), the CO concentrations are improved but still non-compliant. However, if lower vehicle emission rates are used (Case 3), the CO concentrations are much lower – the vast majority of the carpark indicates CO levels that are less than the 60ppm criterion. Although there exists a high-CO area at the upper-left side, this is caused by flow re-circulation as shown in Figure 3 – it may be argued that vehicles passing through this area would extinguish any re-circulation (due mainly to flow entrainment from moving bodies) and thus the solution would be compliant. With both a higher average car speed and lower emission rates (Case 4) the CO concentrations are lower still.

Although a commercial carpark is considered in this example, the methodology extends to carparks of any usage – this includes mixed-use carparks where the localised CO generated in different parts of the carpark (e.g., residential, commercial or retail) can be proportioned and integrated into the one model.

CO Concentration (ppm)	Case 1 Standard	Case 2 High Speed	Case 3 Reduced	Case 4 Reduced and high speed
Spatial average	50	43	26	24
Spatial maximum	341	296	148	131

Table 5. Comparison of the computed one-hour average CO concentrations.

DESIGN OPTIMISATION

Although the Case 3 and Case 4 results shown in Figure 2 may be considered an acceptable solution, it may be warranted to take full advantage of the Performance Solution and yield a ventilation design that is optimised in terms of providing a compliant

* In this example, the software ANSYS Fluent is used.

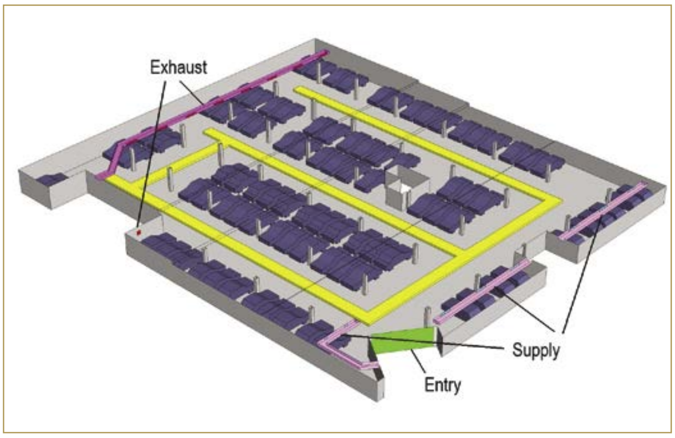

Figure 1. Carpark CFD model.

solution with the minimum quantity of exhaust flow. For this example, an optimised design could comprise the following:

- Deletion of the mechanical supply system;
- Use of the carpark entry for make-up air;
- Removal of the mechanical exhaust ductwork and replacement with a single exhaust point;
- Addition of two jet (impulse) fans to improve the air distribution and lower the CO concentrations;
- Reduction of the total exhaust flow rate by 60% (from 7,700L/s to 3,000L/s).

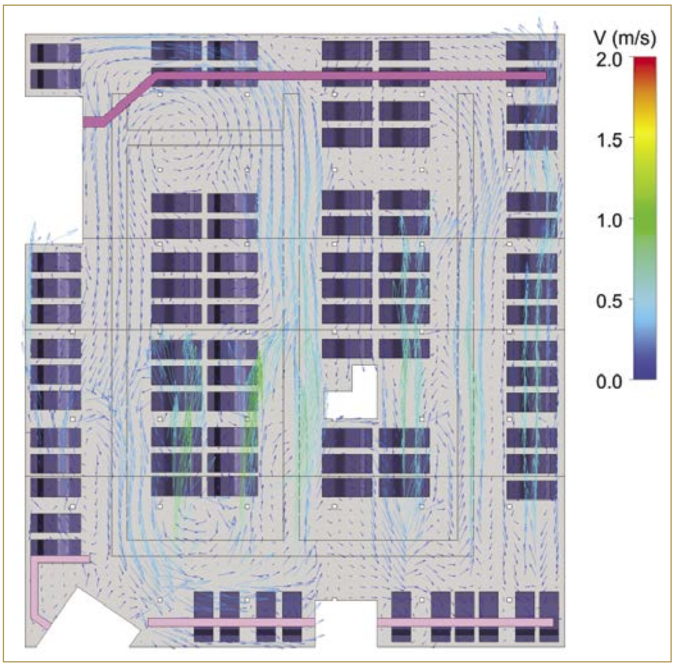

Figure 3. Velocity vectors showing the flow re-circulation zone.

The resultant CO concentrations for this scenario are shown in Figure 4. With the above changes to the design, not only are the maximum CO concentrations compliant (maximum CO of 55ppm) but the substantial reduction in the total exhaust

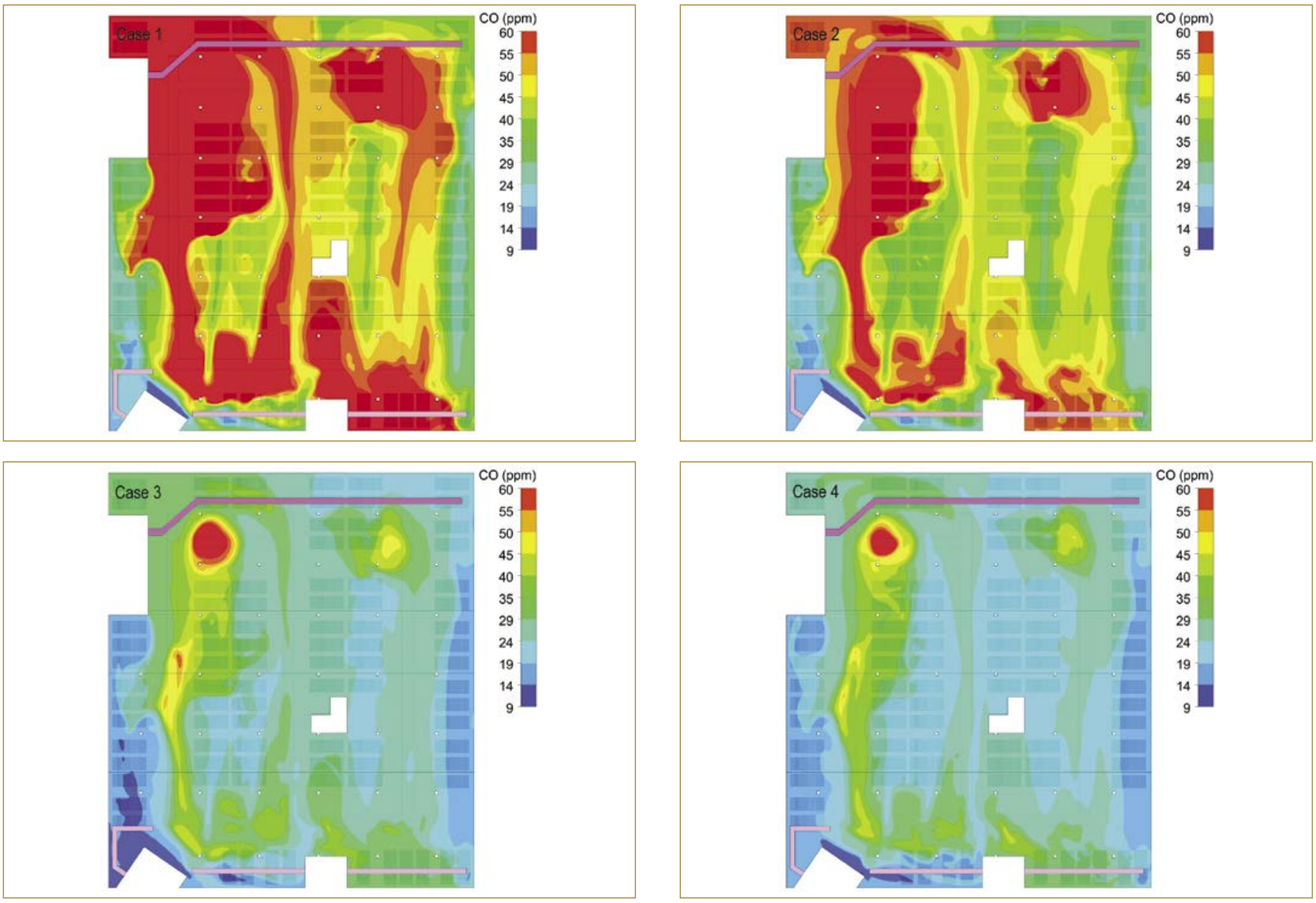

Figure 2. Comparison of the computed one-hour average CO concentrations for the four simulated scenarios.

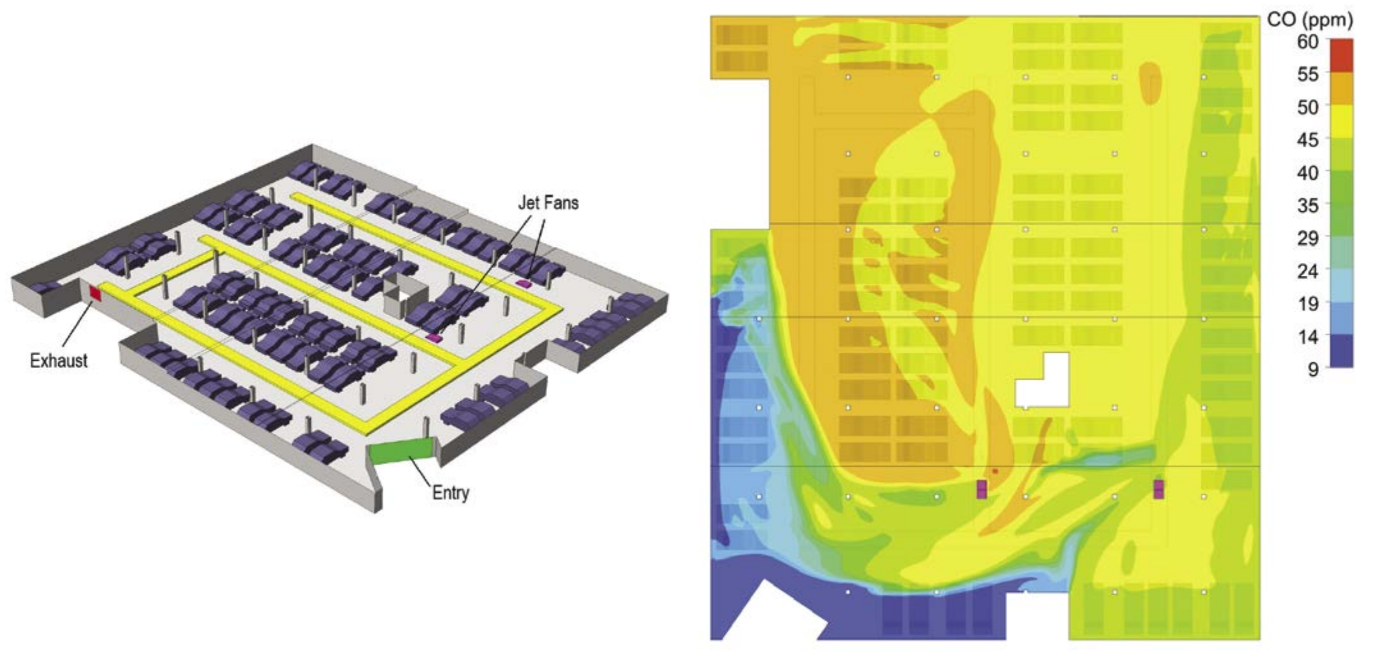

Figure 4. Optimised design with addition of jet fans, removal of supply system and reduction in exhaust flow rate.

flow rate and removal of the mechanical supply system will allow significant reductions in up-front and ongoing costs. Clearly these benefits can be amplified when designing ventilation systems for larger capacity carparks.

CONCLUSIONS

Australia has made great advances in adopting sustainable design and energy efficiency practices in recent times, as evidenced by Section J of the NCC. However, these advancements have not extended to the DtS design of carpark ventilation systems in AS1668.2; in order to apply the latest sustainable design principles a Performance Solution is required.

The DtS pathway is certainly straightforward, and this helps to explain its popularity, but it certainly should not automatically be assumed to result in a well-designed layout. Alternatively, when considering a Performance Solution, it is suggested that the exhaust flow rates calculated using AS1668.2 be used as a guide, since these flow rates can be over-conservative when considering modern vehicle fleets and the ever-increasing improvements in vehicle emission controls.

It can be simple enough for a capable engineer to design a Performance Solution utilising some of the principles discussed here, but the effort may be futile if the respective certifier is not on board with the solution. It is therefore incumbent on all parties to become more familiar with the Performance Solution approach and to be mindful of the significant benefits that can be realised with this method. ▮

ABOUT THE AUTHOR

Dr Craig Pregnalato, M.AIRAH

Dr Craig Pregnalato, M.AIRAH, is a director at Desanco. He has been working in the built environment for more than 15 years, with particular expertise in CFD modelling and analysis.

REFERENCES

1. *National Construction Code Volume One – Building Code of Australia*, Australian Building Codes Board, 2019
2. *Australian Standard: AS1668.2-2012 The use of ventilation and airconditioning in buildings Part 2: Mechanical ventilation in buildings*, Standards Australia, 2012
3. Smit, R. & Ntziachristos, L., Cold Start Emission Modelling for the Australian Petrol Fleet, *Air Quality and Climate Change*, vol. 47 no. 3, August 2013
4. Singer, B.C, Kirchstetter, T.W, Harley, R.A, Kendall, G.R. & Hesson, J.M, A Fuel-Based Approach to Estimating Motor Vehicle Cold-Start Emissions, *Journal of the Air & Waste Management Association*, 49:2, 1999
5. Australian Bureau of Statistics: *9309.0 – Motor Vehicle Census*, Australia, 31 Jan 2019
6. *Summary of Emission Requirements for New Petrol Passenger Cars in Australia 1972 – 2018*, Australian Government Department of Infrastructure, Transport, Regional Development and Local Government, 2018
7. Favez, J, Weilenmann, M. & Stilli, J, Cold start extra emission as a function of engine stop time: Evolution over the last 10 years, *Atmospheric Environment*, vol. 43, 2009
8. *Traffic Engineering Manual Volume 3 – Speed Zoning Guidelines*, VicRoads, ed. 1 June 2017
9. Inquiry into Pedestrian Safety in Carparks, *Report of the Road Safety Committee on the Inquiry into Pedestrian Safety in Carparks, Parliamentary Paper No. 311 Session 2006–10*, 2010
10. *State of the Air in Australia*, Department of Sustainability, Environment, Water, Population and Communities, Commonwealth of Australia, 2010
11. *Air Monitoring Report 2018 – Compliance with the National Environment Protection (Ambient Air Quality) Measure*, Environment Protection Authority Victoria, October 2019