Optimization of the trench opening area for a naturally ventilated railway station with diesel trains

Y. Liu
Parsons Brinckerhoff, Australia

M. Vasilovska
Sinclair Knight Merz, Australia

ABSTRACT

New railway stations within densely populated urban areas are usually built below ground within an open or semi-enclosed trench configuration to create more space for pedestrian and traffic use at surface level. This paper analysed the impact of cantilevers on air quality at platform level and within train carriages when diesel trains are passing through or stopping at naturally ventilated stations without and with a side wind of 2.5 m/s for the following configurations:

- Fully open trench, and
- Partially covered trench with varied cantilevers on each side ranging between 2 m and 5 m wide.

Keywords: Natural ventilation, trench, railway station, emissions, CFD, diesel engine, train.

Abbreviations

ACU	Air Conditioning Unit
CFD	Computational Fluid Dynamics
CO	Carbon monoxide
DL	Diesel Locomotive hauled commuter train
DMU	Diesel Multiple Unit, a commuter train consisting of multiple carriages powered by one or more on-board diesel engines
FDS	Fire Dynamics Simulator
NIST	The US National Institute of Standards and Technology
NO_x	Nitrogen Oxides
NO_2	Nitrogen Dioxide
PM_{10}	Particulate matter with size under 10 micrometres

1 INTRODUCTION

Diesel powered passenger trains are still being used on non-electrified rail lines in a number of countries. They feature a much lower capital expenditure without requiring electrification of existing rail lines. However, diesel powered engines generate emissions and design of naturally ventilated underground railway stations complying with the air quality standards that are becoming stricter is a challenge for engineers. On the other hand, natural ventilation of new railway stations and tunnels is of an increasing interest due to the recent attention to environmental issues and the benefits of reduced lifecycle costs.

This study analysed the air quality within fully opened and partially enclosed trenched stations with cantilevers on both sides ranging from 2 m to 5 m wide. This trenched station serves as a railway station for diesel powered passenger trains in a densely populated urban area. Flat horizontal cantilevers on both sides of the trench have been proposed to allow the surface areas above the cantilever to be used as pedestrian and cycling paths. Glass panels approximately 2.7 m high have also been assumed at cantilever ends to minimize the direct exposure of pedestrians and cyclists to the diesel emissions from the trains below. The objective of these analyses was to assess the impact of cantilever depth on air quality at station level and within train carriages and find an optimal design solution for natural ventilation achieving acceptable air quality to satisfy regulatory standards, whilst extending the usable space at street level.

Computational Fluid Dynamics (CFD) modelling using Fire Dynamics Simulator (FDS) was adopted to optimize the dimension of the cantilevers on both sides of the tunnel trench. The three main pollutants – CO, NO_x and fine particulate matter (PM_{10}) have been assessed and were monitored at selected critical locations such as at ACU intakes and at platform 1.5 m above the floor level. Occupants considered in this investigation include those who are waiting at platform and those who are staying inside the train while the train is idling at the station. Air quality modelling was performed for each trench configuration and natural ventilation without wind and with side wind of around 2.5 m/s. The air quality results for each pollutant were compared for compliance with the air quality standards.

This preliminary investigation revealed that the opening area of a partially enclosed trenched railway station has a big impact on the effectiveness of the natural ventilation and its compliance with air quality standards. Performance based ventilation assessment was used for optimisation of cantilever widths. The analyses indicated that type and size of diesel train engines, dwell times at stations and details of the ACU systems need to be considered and carefully analysed when planning a partially enclosed railway station below the ground surface.

2 AIR QUALITY ACCEPTANCE CRITERIA

Background air quality used for the modelling is summarized in Table 1 below. This is the assumed background air quality without the influence of diesel train emissions discussed in this investigation.

Table-1: Background concentration of CO, NO_x and PM_{10}

Pollutant	Background concentration
CO	10 ppm
NO_2	0.03 ppm
PM_{10}	20 µg/m³

The CFD modelling only calculated the pollutants increase above ambient level by specifying a zero background pollutants concentration. To allow a direct comparison with the CFD modelling results, the acceptable pollutants concentration increase above ambient due to diesel train engine emissions is required. An oxidation rate of 10% for NO_x emissions into NO_2 was assumed as usually used for tunnels and confined spaces.

The air quality acceptance criteria used in this modelling and the allowable concentration increments above ambient for CO, NO_2 and PM_{10} are summarised in Table 2 below.

Table-2: Air quality acceptance criteria

Pollutant	Time Average	Air quality limit	Pollution increase above background
NO_x within train & on platform	1 hr	1.1 ppm	0.8 ppm
PM_{10} within train	24 hr	50 µg/m³	30 µg/m³
PM_{10} on platform	24 hr	33 µg/m³	13 µg/m³

3 COMPUTER MODELLING

3.1 General

Fire Dynamics Simulator (FDS), computational fluid dynamics (CFD) software, was used for computer modelling of pollutants transport. FDS was originally developed by the US National Institute of Standards and Technology (NIST) in 2000 for fire-driven fluid flows [1]. FDS numerically solves a form of the Navier-Stokes equations for low speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The core algorithm is an explicit predictor-corrector scheme, second order accurate in space and time. Turbulence is treated by means of the Smagorinsky form of Large Eddy Simulation (LES).CFD is considered applicable for modelling of any thermal driven flows and other room air flow problems [2,3].

As additional species can be solved by introducing additional scalar transport equations, transient 3-D transport of pollutants (PM_{10}, NO_x and CO) were modelled, and buoyancy effects were incorporated in the modelling.

Fine grid resolution of 0.1m was placed near the train emission source, and relatively coarse mesh of about 0.2m was used for other regions. The number of total computational cells is about 1.4 million. CPU time for parallel computing using two processors was about 3 days for each trench configuration. A grid resolution checks were performed by using coarse mesh size of 0.5m in the longitudinal direction. The results showed extra high pollutants concentrations on the platform and at the ACU intakes indicating an existence of artificial diffusion when using coarse mesh of 0.5m.

Stationary trains were simulated for duration of 300 s in this modelling. It was assumed that the DMU is idling at the station for 120 s (2 min) and the DL is idling for 300 s (5 min) before accelerating out of the station. In the CFD modelling, the leaving trains were realized by removing all the train carriages (in this case there is only one carriage per DMU / DL trains) and switching off all diesel engines and ACU intakes..

To account for the influence of the ACU on the in-train air quality, air pollution concentrations at outside air intake points were measured. Train walls in the CFD model were constructed from metal with zero thickness. Airflow inside the train carriage was generated by a fixed exhaust rate of 1.2m^3/s through one 0.5m x 0.5m opening per carriage located on the opposite wall from the ACU intakes with an average air discharge velocity of 4.8 m/s. The specified exhaust air draws outside air to ACU units through two 0.5m x 0.5m outside air intakes (~ 0.6m^3/s each generating average air intake velocities of 2.4 m/s) that are specified by an open boundary condition.
When the train is idling at a station, the total mass flux of emissions was assumed to be discharged through a 0.3m x 0.3m opening located on the roof of the train with discharge velocities of about 0.5m/s for the DMU (engine idling), and 6 m/s for the DL (engine full load).

A side blowing wind with an average wind velocity of 2.5m/s has been assumed. Outdoor ambient air temperature of 20°C was used. It is noted that the background pollutants concentration has been assumed as zero (0) in the modelling and the modelling results of pollutants are the actual increments above ambient values.

3.2 Train data

Two types of diesel passenger trains were used in the analyses – Diesel Multiple Unit (DMU) and Diesel Locomotive (DL) hauled trains. The two train types have a dimension of 20m long x 2.8m wide x 3.85m high.

The train engine data for each train type is summarised below. The DMU main engine data was assumed to be from a carriage pulling the train, but idling at the station. The DL engine was assumed to be from a passenger carriage adjacent to a locomotive pulling the train. Refer to Section 3.4 for clarification of assumptions used in the modelling.

Table-3: Specifications of trains

	DMU car engine	**DL car engine**
Idling time	120 s	300 s
Engine size	410 kW	170 kW
Throttle Position	Idling	Position 8 (maximum)
Fuel consumption rate	0.89 g/s	10.56 g/s
Excessive air	46 %	46 %
Total emission mass flow	0.0483 m^3/s	0.5734 m^3/s
CO emissions	159.8 g/hr	690.2 g/hr
NO_x emissions	310.67 g/hr	3196.00 g/hr

PM_{10} emissions	47.25 g/hr	227.80 g/hr

Emissions in Table-3 are calculated based on the assumed fuel consumption and the excessive air. The excessive air is the extra air that is drawn into the engine cylinder but not used in the combustion process. The DL car was assumed to be always at full power because it needs to power its ACU system and train lighting. The DMU engine was assumed to be in idling throttle position when stopped at platform.

Mass flow rate of the emission stream was obtained by explicitly calculating all the combustion species. If the diesel can be represented by $C_{12}H_{23}$, chemical reactions for the combustion of diesel fuel can be simplified by the formula below on which the calculation of species was based:

$$C_{12}H_{23} + 17.75O_2 + 71N_2 + \text{Excessive Air} = 11.5H_2O + 12CO_2 + 71N_2 + \text{Heat}$$

Total mass flow and mass fraction of CO, NO_x and PM_{10} were used as inputs for the computer model. Constant generation rate of CO, NO_x and PM_{10} were specified as boundary conditions for the CFD modelling. The temperature of the emission mass flow stream was assumed to be 170°C.

Trains had fixed windows but equipped with air conditioning units (ACU) providing cooling and outside air supply to the passengers. Two ACU intakes, sized 0.5m x0.5m each, were assumed for each car. The DMU trains have ACUs with outside air intakes located on the roof of the trains, and the outside air intake of the ACUs for the locomotive hauled trains is from below the train floor.

3.3 Design cases

CFD modelling was performed for trenched stations with different cantilever widths as summarised in Table 4 below.

Table-4: List of cases investigated

Case No.	Cantilever width on each side of the semi-opened trench station
1	0 m
2	2 m
3	3 m
4	5 m

The cross sections of the underground station with varied cantilever widths are shown on Figure 1. The corresponding pictures on the right hand side of each trench configuration are snapshots of the computer model with smoke visualization. In most cases only one train stops at the station. However, a worst case scenario was modelled when two trains - one DMU and one locomotive are idling at the station at the same time for 120s until the departure of the DMU. The locomotive is idling for a further 180s.

To reduce the computational time without decreasing the accuracy of the modelling result, the whole train is represented by a single train car for the research purpose. A 40m long rail trench section is selected as computational domain for the modelling. The overall dimensions of the computational domain are 40m (L) x 18.7m (W) x 10.3m (H).

The height includes additional 2m above the 2.7m high glass panel to impose the wind boundary condition. As shown in Figure 1, this section includes a train car with engine, station platform, cantilevers and cross beams, and vertical shield glass panels on both sides of the trench.

A DMU car on the north rail and a diesel locomotive car on the south rail are longitudinally located in the middle of the computational domain of the trench section, see Figures 2. Emission sources sized 0.2m x 0.2m are centrally located on the roof of each vehicle. Total mass flow rate of combustion products is imposed on the surface of the emission source, and the fraction of the CO, NO_x and PM_{10} were specified according to the vehicles fuel consumption specification.

Occupants on the train and on the platform should not be exposed to excessive pollutants concentration. As the trains have sealed windows, the pollutants can enter the train carriage via the outside air intake points of t he air conditioning units (ACUs). Therefore, the pollutant concentrations are recorded at the ACU intakes of the trains and at 1.5m above the platform floor level. The monitoring locations are indicated on Figures 1 & 2.

3.4 Assumptions and limitations

CFD modelling was based on few assumptions and simplifications as described in this section. The analyses is limited to a simple comparison of the impact of diesel engine pollution on air quality affecting passengers within train carriages or waiting at platform in a semi-enclosed trench configuration with varying cantilever depths. The aim was to show the impact of diesel train types and cantilever depths on air quality affecting passengers at naturally ventilated station platforms located below ground level.

The main assumptions in this study are summarised below, but will need to be carefully considered when modelling a real project.

- Only two train carriage types were modelled – one DMU car engine and the other one DL car engine. The DMU car engine was assumed as the main engine hauling the train idling at the station, but in real train configuration there will be usually 4-5 cars per train with a combination of main and auxiliary engines. The DL car engine was assumed to be a passenger train car with its own engine powering the lighting and ACUs. The locomotive engine was not modelled as it is expected to be idling at the station and have less impact on air quality. All engine emissions need to be considered when assessing a real project,
- only one trench depth with horizontal cantilevers that can be used as pedestrian paths or cycleway were considered,
- Flow induced by thrust effect was not considered,
- wind blowing at right angle was assumed for research purposes only to assess its impact on air quality,
- Due to lack of detailed information, location of ACU fresh air intakes have been assumed as being located on the roof of the DMU and the bottom of and DL cars. The ACU fresh air intakes could be located on the sides above or below the window level depending on train design.

4 AIR QUALITY ASSESSMENT

CFD modelling results for trenched stations with varied cantilever widths of 0m, 3m, and 5m are graphically presented in Figures 3 to 10. Results for 0m and 2m wide cantilevers are not included as the concentrations of pollutants are too low to be visibly plotted. These low pollutant concentrations are a result of narrow cantilever width, which leaves the emission discharge area directly exposed to the sky and the engine generated emissions will be directly vented out.

Based on the possible location that occupants may stay or pass through, it has been established that concentrations of pollutants on the platform, inside DMU and locomotive, all need to comply with the standards by maintaining a pollutants level that doesn't exceeds its acceptance criteria. To allow a direct assessment against the regulatory standard, CO, NO_x and PM_{10} concentrations have been recorded at the following locations and shown in Figures 1 and 2:

- 1.5m above the platform floor level,
- Outside air intake of ACU for the DMU car,
- Outside air intake of ACU for the locomotive car.

The recorded CO concentrations at the above locations are far below the acceptance limit and are not included in the discussed.

CFD modelling result of fine particle matters (PM_{10}) at 2 minutes for cantilever widths of 0m, 3m and 5m are shown in Figure 1. It can be visualized that the engine generated hot emissions will flow to the higher region in the station trench because of buoyancy. Since DMU air conditioning unit intake is located on the roof, the DMU car will be more likely to take in the polluted air than the diesel locomotive with air conditioning units at carriage floor.

Figure 3 and Figure 4 are the CFD modelling results of the PM_{10} and NO_x concentration, respectively. These pollutant species are recorded at the ACU intake for the DMU for the cases with 3m and 5m wide cantilevers. It has revealed that width of cantilevers have significant impact on the transport of pollutants generated from the engine. Both PM_{10} and NO_x significantly exceed the acceptance limit if 3m or 5m wide cantilever is used. Peak concentration of PM_{10} and NO_x has been recorded at 120s because the species concentration is accumulated within a period of 120s before the DMU vehicle drive out of the station.

Figure 5 and Figure 6 show the CFD modelling concentration of the PM_{10} and NO_x, respectively, these pollutant species are recorded at the air conditioning unit intake for the diesel locomotive for the cases with 3m and 5m wide cantilevers. The results showed that concentrations of both PM_{10} and NO_x are well below the acceptance limit. The ACU of the locomotive car takes much less pollutants because the locomotive ACU intake is located below the bottom of the train, while buoyancy driven flow generated pollutants flow towards the higher region of the semi-open trench. Peak concentration is recorded at 300s as the locomotives remain idling at the station for that period of time.

As DMU and locomotive are located on each side of the platform, their emissions will affect the air quality on the platform affecting commuters waiting at the station. Figure

7 and Figure 8 show the CFD modelling results of the PM_{10} and NO_x, respectively. These pollutant species are recorded at the centre of the platform and 1.5m above the floor level for 3m and 5m wide cantilevers. The results showed that for 5m wide cantilever, there is a short period that the PM_{10} concentration exceeds the acceptance limit, with its peak PM_{10} concentration recorded at 300 s. In the case of a 3m cantilever, both PM_{10} and NO_x remain below the acceptance limit.

Based on the above discussion, PM_{10} concentration inside the DMU vehicle is the dominant pollutant for the design of natural ventilation system. Therefore, the following discussion will focus on PM_{10} concentration at 120 s for the DMU vehicle for different cantilever configurations.

Table-5 shows the recorded time-averaged PM_{10} concentration for cases without and with 2.5 m/s wind. All the values in Table-5 are averaged over 5 min period. If we assumed that the frequency of the train is every 5 min during the peak hours, then these time averaged concentration would become a 1h average value and can be compared for compliance with the 1h average air quality acceptance criteria. For cases with cantilever width of 3m or 5m, higher PM_{10} concentration is recorded in the presence of wind than that without wind. Comparison is made against the acceptance criteria listed on Table-2, and it is recommended that cantilever widths of 3m or 5m are not acceptable based on the excessive pollutant concentration inside the DMU car, as both 1h average and peak PM_{10} concentration exceed the acceptance limit or can not gain a comfortable safety design factor. The reason is that if the cantilever width is more than 2.8 m, it covers the train emission source and the emissions are trapped inside the trench are taken by the air conditioning system.

Figure 9 shows the in-train PM_{10} concentration for a DMU train for varied cantilever widths against the acceptance criteria for scenarios with and without wind. A comparison of the in-train pollutants concentration for the DMU shows that a cross blowing wind has a negative effect on the natural ventilation of the station trench. More emissions are trapped in the trench under the influence of cross wind, which performs like a curtain and generates a street-canyon effect. This suggests that wind impact can not be ignored in the assessment. Figure 9 also clearly shows that an underground trench with 5m wide cantilever will not comply with the air quality criteria. Similarly, Figure 10 shows the in-train air quality for a DL train, and Figure 11 represents the air quality assessment at platform level. They both comply with the air quality standards.

Table-5: CFD modelling results summary – maximum PM_{10} increase recorded within DMU, Locomotive and at the platform

Options	1.5 m above the platform level		ACU intakes for DMU		ACU intakes for DL		Pass / Not (Y/N)
	Max.	5-min ave.	Max.	5-min ave.	Max.	5-min ave.	
acceptance criteria limit increase 1-hr average [μg/m³]	13	13	30	30	30	30	
Open trench – no wind	<1	<1	<1	<1	<1	<1	Yes
Open trench –wind 2.5m/s	<1	<1	<1	<1	<1	<1	Yes
2m cover – no wind	<1	<1	<1	<1	<1	<1	Yes

2m cover – wind 2.5m/s	2	<1	<1	<1	<1	<1	Yes
3m cover – no wind	<1	<1	90	14	<1	<1	No
3m cover – wind 2.5m/s	12	2	180	28	<1	<1	No
5.0m cover – no wind	32	7	457	75	<1	<1	No
5.0m cover – wind 2.5m/s	40	6	787	118	8	1	No

5 CONCLUSIONS

Computational fluid dynamics modelling has been performed for performance-based assessment of natural ventilation system for trenched station configurations with varying cantilever widths. This investigation indicated that:

- Opening area of a semi-opened railway station has a big impact on the natural ventilation of the train emitted pollutants. Performance based ventilation assessment needs to be undertaken before a decision is made,
- Considerations of type and size of train engines, dwelling time at the station, operation details of the train's ACU system and ventilation strategy for the station need to be taken into account when planning a railway station below the ground surface,
- Based on the nominated emission rate and the acceptance criteria for the pollutants, it is recommended natural ventilation system for a semi-opened underground railway station in a trench will work if the emission discharge area of the vehicle is not obstructed. Therefore, as guidance, the maximum cantilever size would be measured from the trench wall to the location of emission source ensuring unobstructed vertical discharge of engine emissions,
- Dwelling time of vehicles with ACU intakes located on the roof of the vehicle is more critical, because hot emissions will be more likely to stay in the higher region of the station whilst dwelling at a station.
- Particulate matters are more critical than other species for passanger trains with diesel engines,
- In-train conditions with ACU intakes located on the train roof are more critical for in-train when compared with ACU intake located near the train bottom,
- Air quality on platform measured at 1.5m above floor level would comply for any cantilever configurations that have been discussed in this paper.

ACKLEDGEMENT

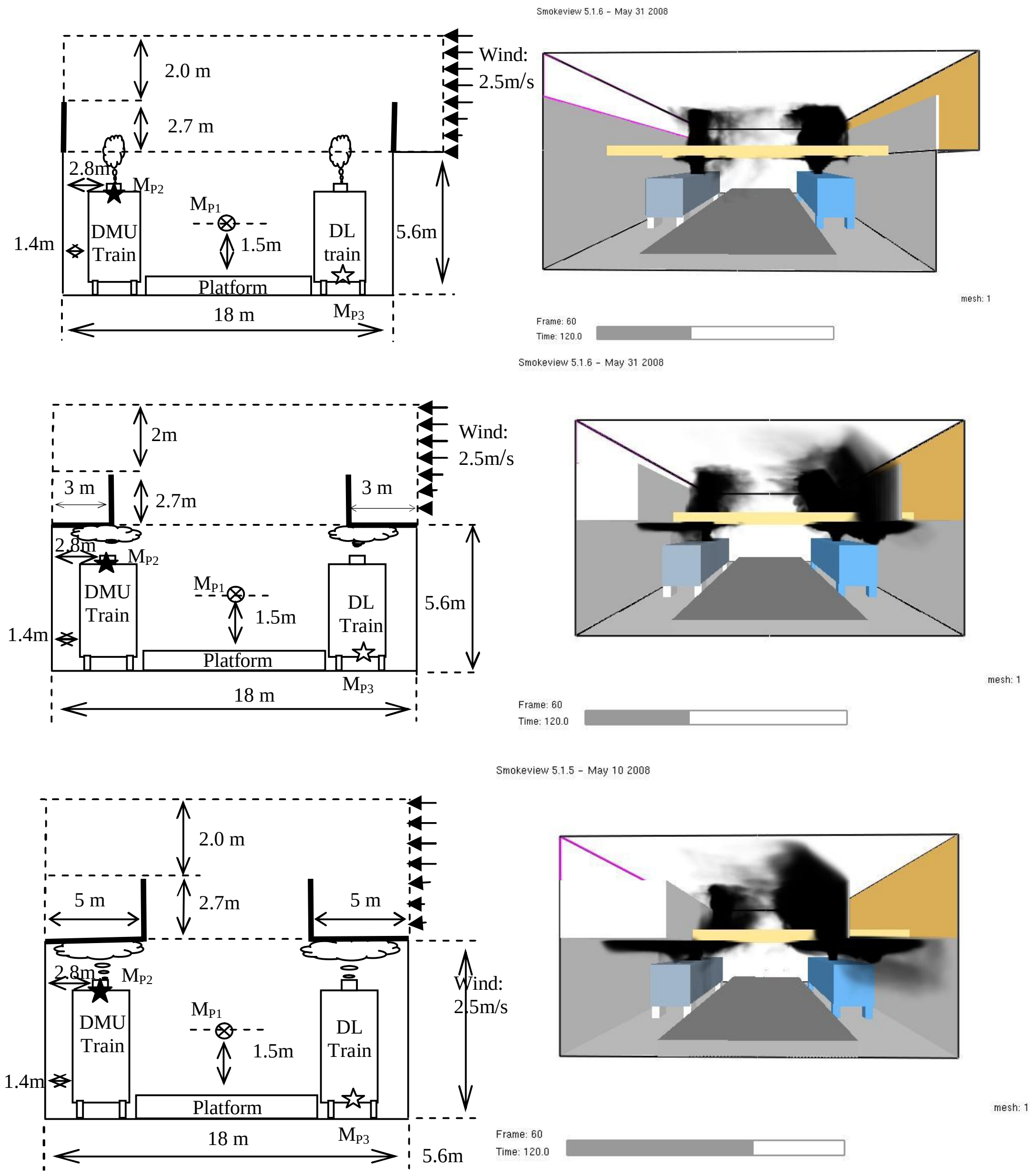
While preparing the draft of this paper, we received help from Chris Chen who gathered the reference material for calculating emissions, and John Munro who commented on the abstract of this paper. Major part of this paper was prepared when M. Vasilovska was an employee of Parsons Brinckerhoff, Australia.

REFERENCES

[1] McGrattan K. and Forney G.P.,2008. “Fire Dynamics Simulator (Version 5) User’s Guide,” *NIST Special Publication 1019-5, National Institute of Standards and Technology, Gaithersburg, MD.*

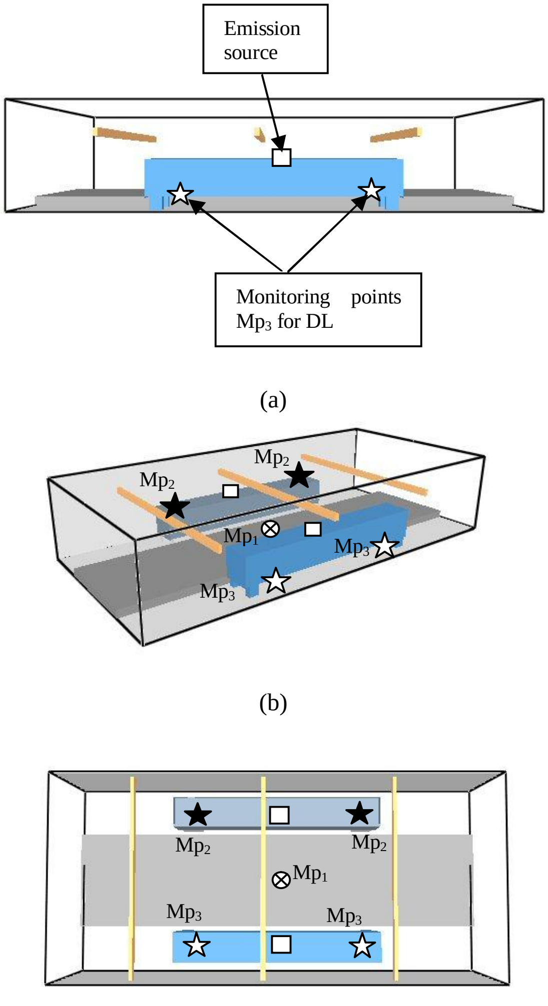
[2] Musser A. McGrattan K. and Palmer J., June 2001. “Evaluation of a Fast, Simplified Computational Fluid Dynamics Model for Solving Room Airflow Problems”, *NISTIR 6760, National Institute of Standards and Technology, Gaithersburg, MD., USA* .

[3] Kriksic F., Phillips D.A., Thompson Z G.P. and Grella J.J.,2006. “Development of an exhaust fume collection system for an existing railway overbuild tunnel”. *BHR Group, 12th International Symposium on Aerodynamics and Ventilation of Vehicle Tunnels*.



Railway station in an open trench, semi-open trench with 3m, 5m cantilever with wind of 2.5 m/s. Symbols ⊗, ★ and ☆ refer to the species concentration monitoring points at Mp1, MP2 and Mp3, which are located at 1.5m above the platform, at the ACU intake of DMU and DL, respectively.

Figure 1: Cross section of trenched station configurations and their respective computer models



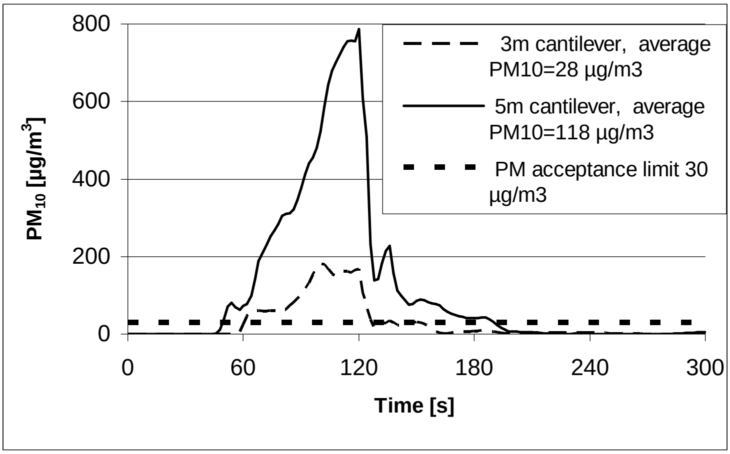
(a)

(b)

(c)

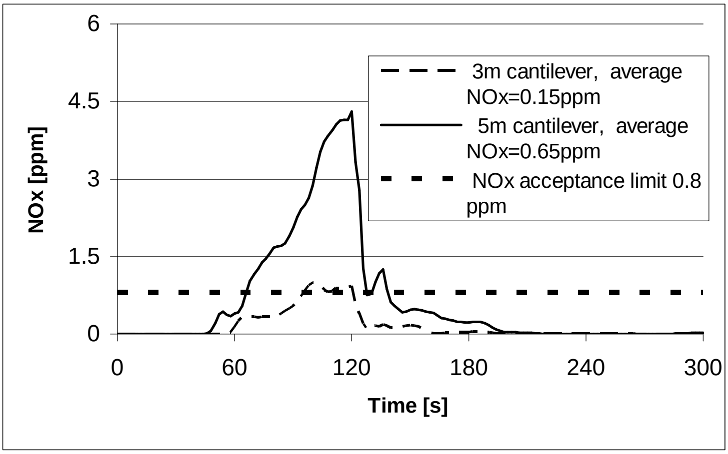
Emission source and the monitoring locations are marked with symbols: Symbols □ refers to the emission source, and symbols ⊗, ★ and ☆ refers to the monitoring point on the DMU roof and bottom of the DL, respectively

Figure 2: Typical computational domain, DMU/DL train configurations, and location of monitoring points



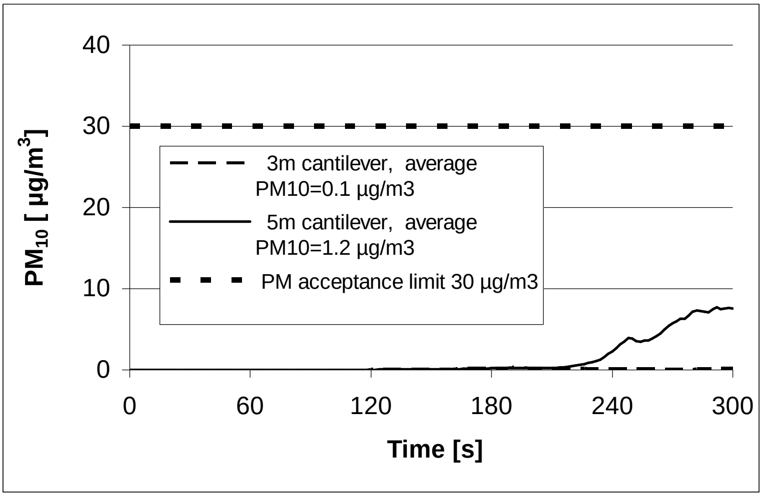
PM_{10} concentration for 3m and 5m cantilever at the ACU intakes of DMU car against the acceptance limit increase above ambient for 1-hr average criteria

Figure 3: PM_{10} pollution levels inside DMU with 2.5 m/s cross wind



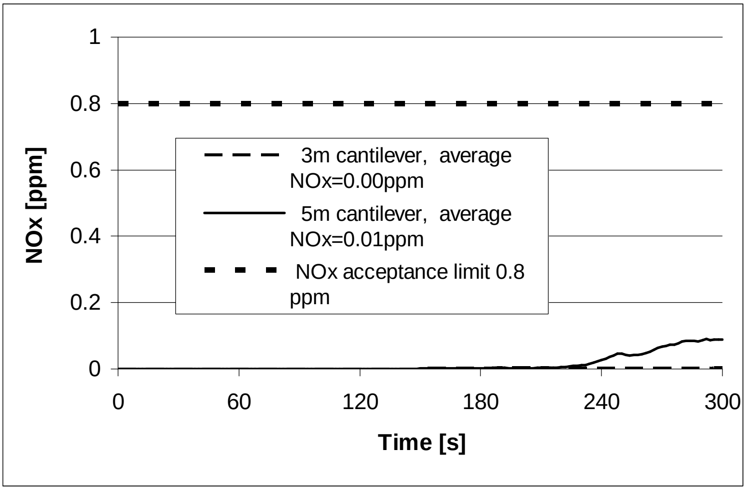
NO_x concentration for 3m and 5m cantilever at the ACU intakes of DMU car against the acceptance limit increase above ambient for 1-hr average criteria

Figure 4: NO_x pollution levels inside DMU with 2.5 m/s cross wind



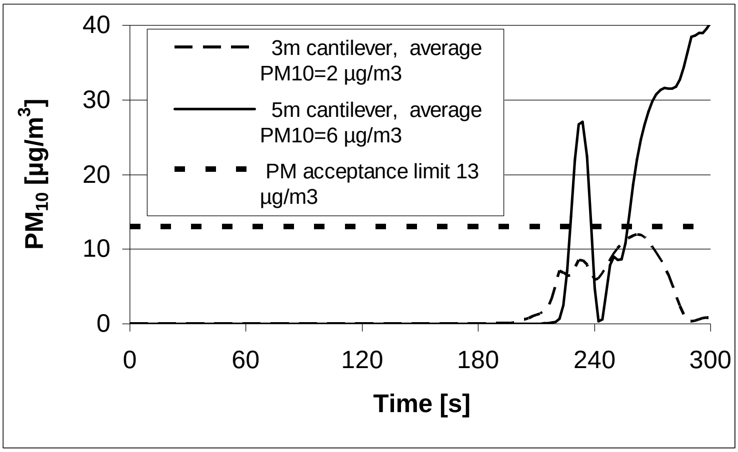
PM_{10} concentration for 3m and 5m cantilever at the ACU intakes of DL car against the acceptance limit increase above ambient for 1-hr average criteria

Figure 5: PM_{10} pollution levels inside DL with 2.5 m/s cross wind



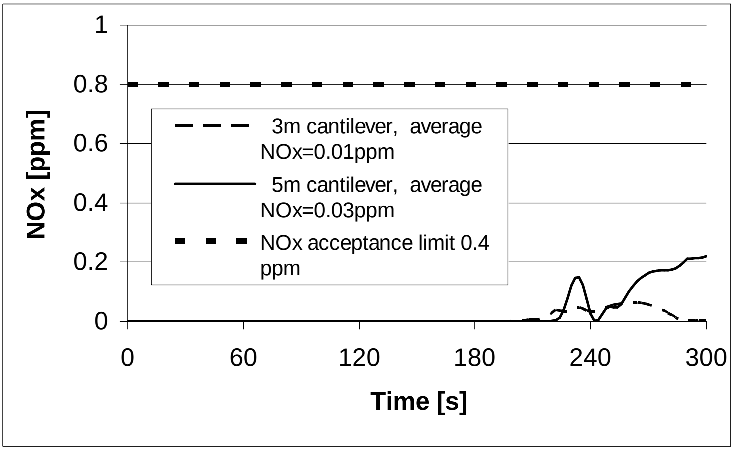
NO_x concentration for 3m and 5m cantilever at the ACU intakes of DL car against the acceptance limit increase above ambient for 1-hr average criteria

Figure 6: NO_x pollution levels inside DL with 2.5 m/s cross wind



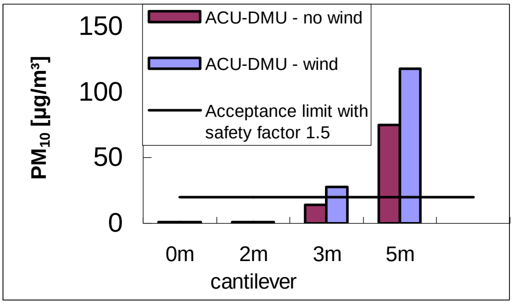
PM_{10} concentration for 3m and 5m cantilever at 1.5m above the platform against the acceptance limit increase above ambient for 1-hr average criteria

Figure 7: Pollution level 1.5 m above platform with 2.5 m/s cross wind



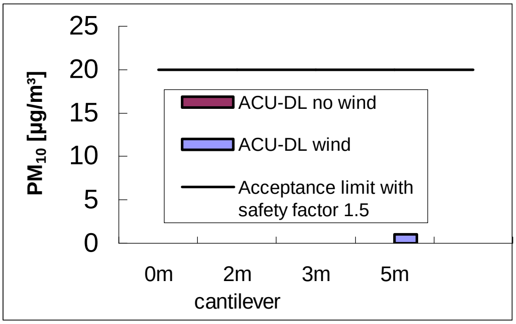
NO_x concentration for 3m and 5m cantilever at 1.5m above the platform against the acceptance limit increase above ambient for 1-hr average criteria

Figure 8: Pollution level 1.5 m above platform with 2.5 m/s cross wind



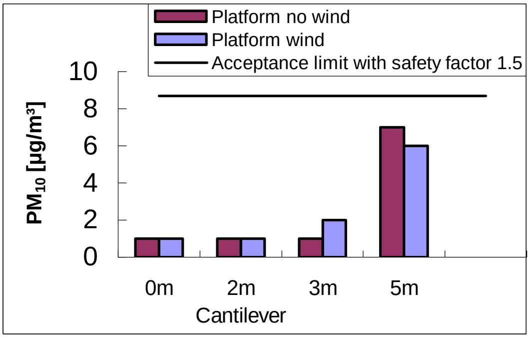
Assessment of in-train PM_{10} against allowed increase above ambient based on 1-hr acceptance criteria with a safety factor of 1.5

Figure 9: Assessment of PM_{10} inside DMU



Assessment of in-train PM_{10} against allowed increase above ambient based on 1-hr acceptance criteria with a safety factor of 1.5

Figure 10: Assessment of PM_{10} inside DL



Assessment of on-platform PM_{10} against allowed increase above ambient based on 1-hr acceptance criteria with a safety factor of 1.5

Figure 11: Assessment of PM_{10} at 1.5m above platform