3D Modelling of Pollutant Dispersion and Exposure around Bus Stop Shelters

Final Project Report, December 2021

Part of the TRANSITION Clean Air Network (UKRI)

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Acknowledgments

This project has been carried out by Oxford Brookes University, in collaboration with Birmingham University, Oxford University and Clean Channel UK Limited; the project was supported by Oxford City Council and Oxford County Council.

The project was funded by the TRANSITION Clean Air Network through the first round of its Discovery & Innovation Fund in 2021. TRANSITION is a UK-wide network, led by the University of Birmingham in collaboration with nine universities and over 20 cross-sector partners, aiming to optimise the air quality and health outcomes of transport decarbonisation. The network (NERC ref. NE/V002449/1) is itself funded by UK Research & Innovation through its Clean Air Strategic Priorities Fund, administered by the Natural Environment Research Council.

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Project Summary

The vast majority of vehicles on UK roads today are of Euro 5 standards or below and represent a significant source of NOx and Particulates (PM); as traffic levels continue to rise, with a projected increase between 17% and 51% by 2050, PM will continue to pose a significant threat to public health even in the context of transport decarbonisation, due to the impact of non-exhaust emissions (from brakes and tyres). Emissions from moving traffic disperse into the air and, depending on local environmental conditions, may cause momentary high-intensity exposure for the public occupying the road side. The health concerns associated with exposure to emissions, even short term exposure, are serious and wide ranging.

Oxford Brookes University have developed a new, high-definition 3D Computational Fluid Dynamics (CFD) modelling tool, capable of predicting the complex dynamics of pollutants' dispersion from moving traffic in localised urban scenarios, and of quantifying actual exposure for the public occupying the space. After performing an initial model validation using purposely-collected field data, this project focused on modelling personal exposure to traffic-related NOx emissions in and around a range of bus stop shelters, based on a realistic open-road urban setting. The aim of the study has been to assess the effective protection shelters offer from momentary, high-intensity NOx exposure and how simple design and orientation modifications may reduce this.

Impact

The World Health Organization recognises that both pollutants' concentration and time of exposure are important in determining the negative health impact of air pollution. Short term, repeated exposure to very high pollutant concentrations – typical at the road side in urban areas – may pose a serious public health concern and more quantitative data are necessary to establish the entity of the problem. Air Quality Monitoring Stations (AQMS) do not routinely measure momentary peaks of NOx or PM, and therefore personal exposure is generally underestimated. Recent published work indeed challenges the current point-fixed, uniform model of exposure based on AQMS measurements.

The high-resolution, time-based, 3D CFD modelling tool demonstrated by this project, has multiple impactful purposes: firstly, it facilitates an improved understanding and quantitative account of actual exposure in localised urban settings; secondly, it can be deployed as a urban planning and diagnostic tool as it provides the ability to combine different urban architectures, traffic patterns and environmental (e.g. wind) boundary conditions. As such, it can be used to estimate the impact of both active (e.g traffic strategies) and passive (e.g. barriers) exposure mitigation measures, providing a legitimate basis for policy makers, local authorities and urban planners to propose changes.

The results of the analysis show how the emissions from Euro 5 diesel vehicles travelling at constant speed convert into high momentary exposure for pedestrians at bus stop shelters; and how shelter's design and orientation can effectively mitigate exposure. The work is continuing as a collaboration between OBU and shelters' provider Clean Channel. The potential applications of the OBU modelling tool are truly numerous; each of them may contribute to a better management of the impact of urban air pollution.

Aim and Deliverables

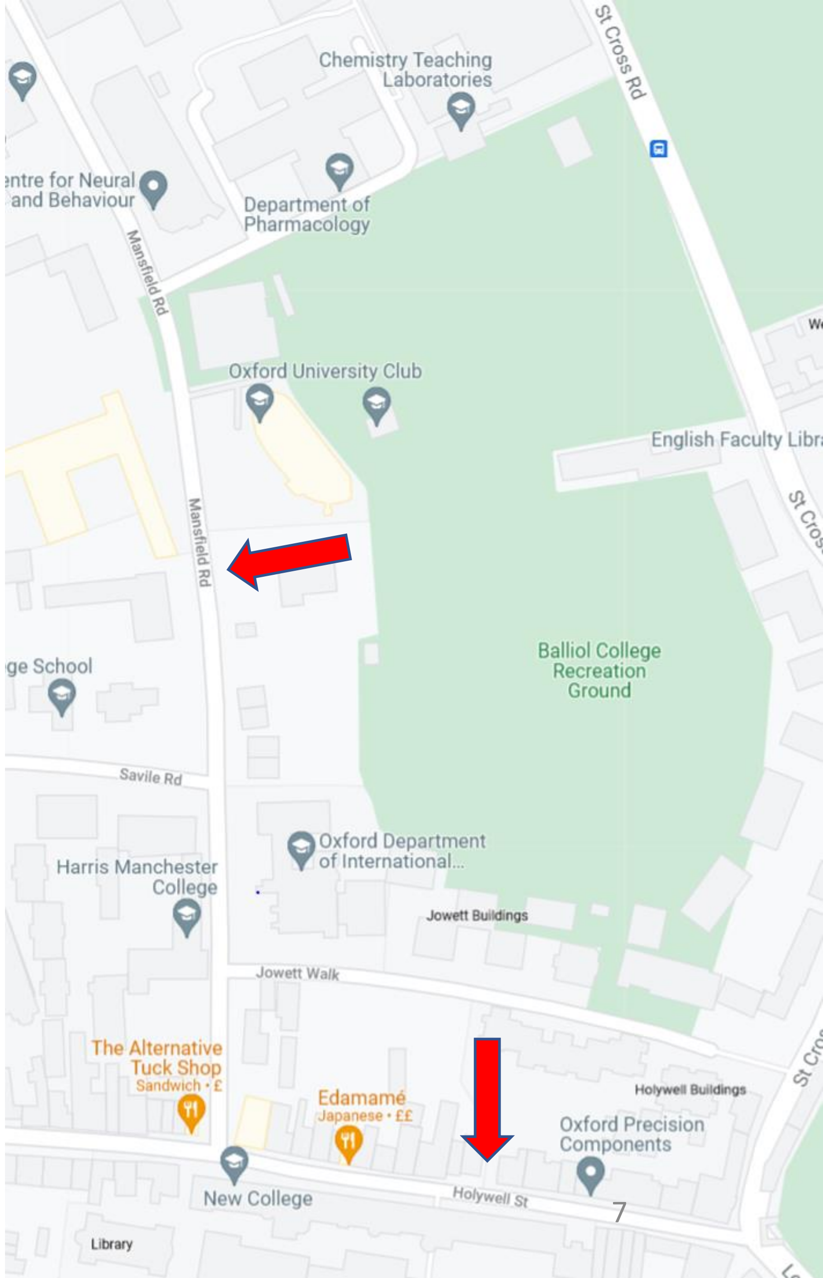
The aim of this short-term project was to further develop the existing high-resolution OBU model of traffic-related pollution and momentary exposure, and to use it to investigate personal exposure at bus stops, contributing to the TRANSITION Clean Air Network effort to characterise newly emerging challenges associated with transport decarbonisation and to protect the vulnerable public.

Deliverables

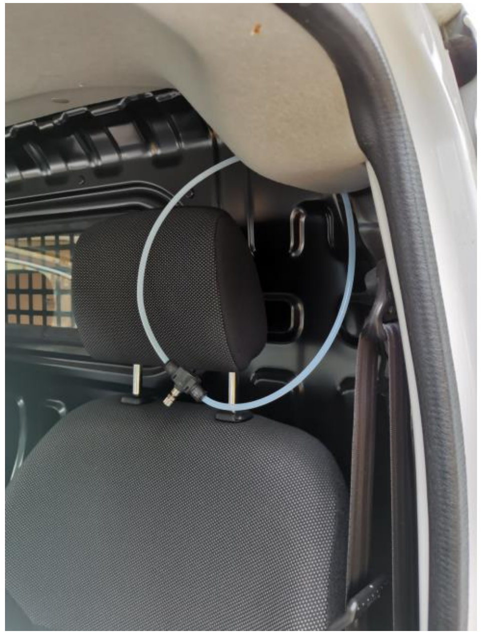
- An leaner CFD modelling protocol, that reproduces greater physical and geometrical complexities over extended physical time.
- Validation of the CFD model against street measurements.
- An assessment of current and new, feasible bus stop shelter designs, in relation to the protection they offer from personal exposure.

Experimental Campaign

- Location:
  Oxford City Centre, Mansfield Road and Holywell street
- Date and Time:
  29 June 2021; 10:00 – 16:00.
- Street Types:
  Semi-Open street (Mansfield Road) and street canyon (Holywell street)
- In consultation with the Oxford City and Oxfordshire County Council, the locations have been chosen as representative of two typical street types in Oxford benefiting from a relatively quite and calm traffic. The purpose was to obtain a (semi-) controlled traffic environment but with real street configuration.
- Emission Source:
  An Electric Van equipped with a bottle of NO mounted on the rear side.
  The bottle contained 10000 ppm of NO in N2 @ 200 bar.
  The van was driven at constant speed of 20 mph while 4.5 mg/m3 of NO was released (similar to the level of NO produced by a Euro5 car running in steady-state conditions).
- Measurements:
  Road-side measurements carried out using Cambustion's fast response NOx system.
  Measurements taken at multiple locations of each street within a fixed distance.



Experimental Campaign



- The aim of the campaign was to release a known amount of NO from a moving vehicle and measure the dispersed NO by the roadside on the pedestrians pathway – in a (semi-) controlled environment.
- A 6 mm rubber pipe used as an ‘exhaust pipe’ releasing NO from the bottle.
- Controlled via a valve in the passenger cabin, NO was released for a duration of 11 seconds covering 100 m of marked distance in the street with the van cruising at 20 mph constant speed.
- The NO sensor was fixed on the pavement on a tripod at a known location.
- In each location, measurements were carried out at two heights of 1.7 m and 1.3 m.
- Wind speed, direction and air temperature also measured locally.
- 69 repetitions of measurement were recorded between the two streets.

CFD Model Development and Main Features

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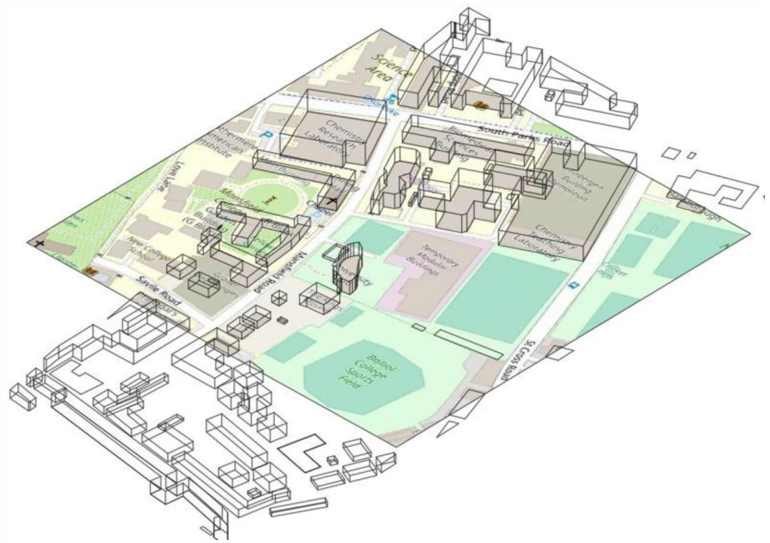
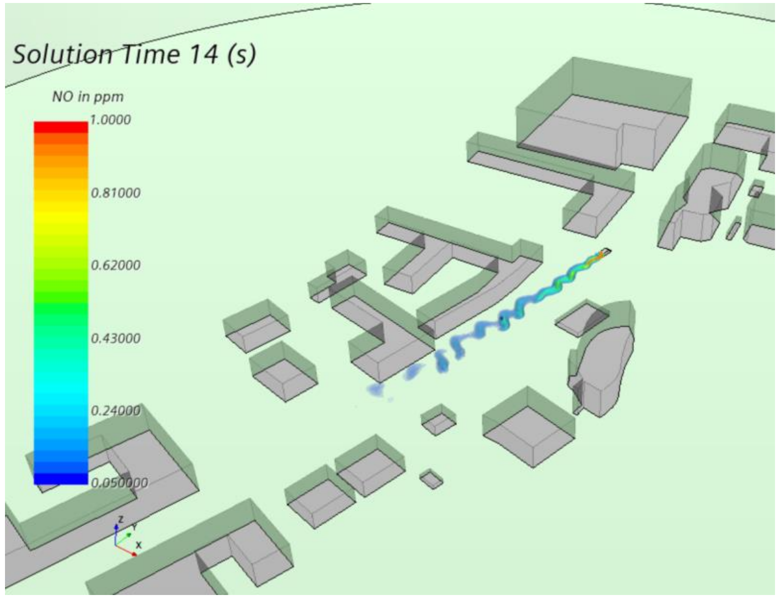
LiDAR → GIS



GIS → CAD



CAD → CFD

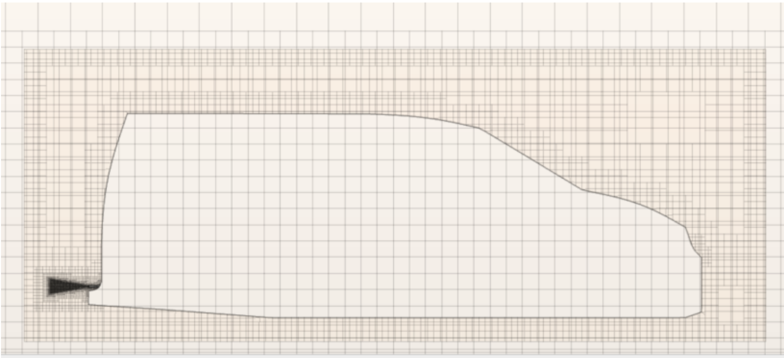
- For the purposes of model validation, large scale CFD models of the relevant Oxford city centre areas were created
- The model was created based on the real street configuration. This was achieved using EA LiDAR data of the area with 1 m resolution. Using GIS open-source software QGIS, the LiDAR data was translated into a 2D layout of the areas, also providing the average height of buildings. This was then converted into a 3D CAD model and then imported into Star-CCM+ CFD software for gas dispersion modelling.
- In order to achieve maximum accuracy in the modelling of flow distribution and gas dispersion, the 'Adaptive Mesh Refinement' method was used which optimises mesh refinement around the path of the moving vehicles, while producing relatively coarser mesh in far field. Mesh independency tests were carried out.

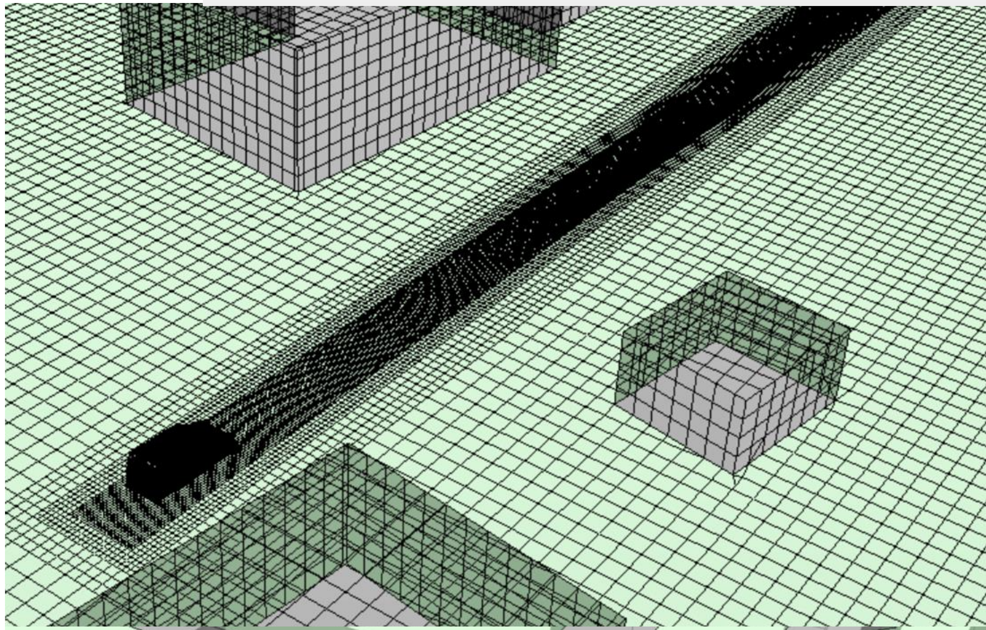
CFD Model Development and Main Features

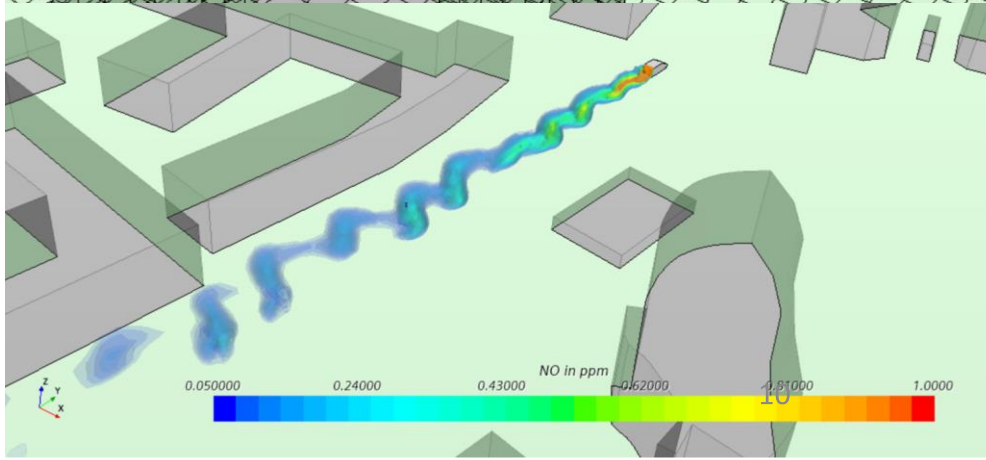
The high-resolution 3D CFD model developed at OBU features relatively simple physics but a complex adaptive domain meshing approach to accurately model the dispersion of pollutant gases from moving traffic.

Main Model Features:

- Multi-Component Gas
- Realizable $k-\varepsilon$ Turbulence Model
- Transient Wind Speed input (as boundary condition)
- Adaptive Mesh Refinement
- Overset Mesh with further refinement over the specified path of the moving Van
- Mesh base-size 2 m
- Mesh refinement around the vehicle 0.2 m
- Overset Mesh Size 0.05 m
- Total Mesh Size 5 million (Mansfield Road)
- Total Run Time 12hrs on 48 computing cores



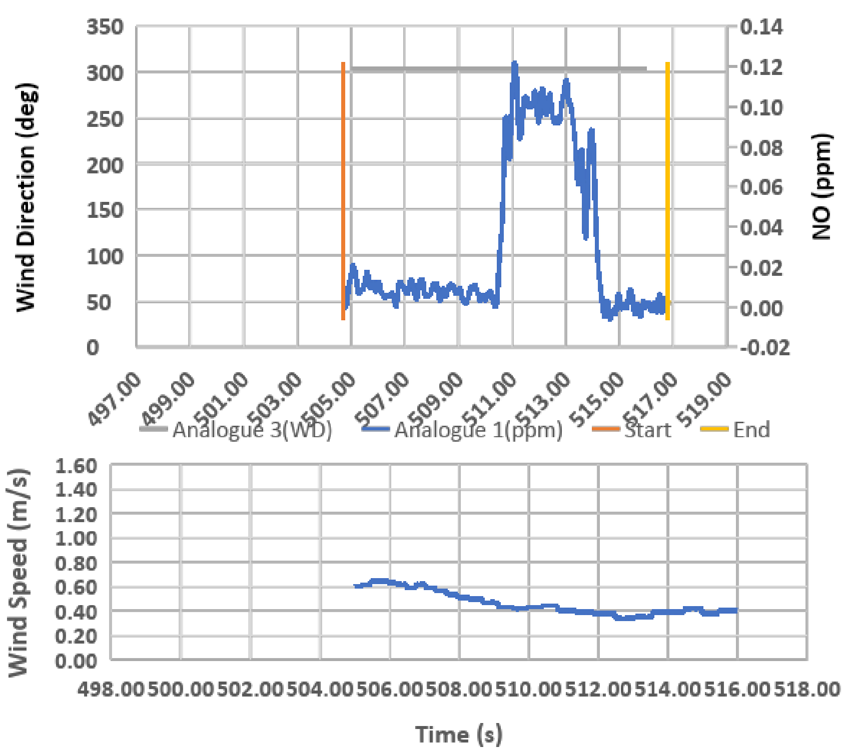


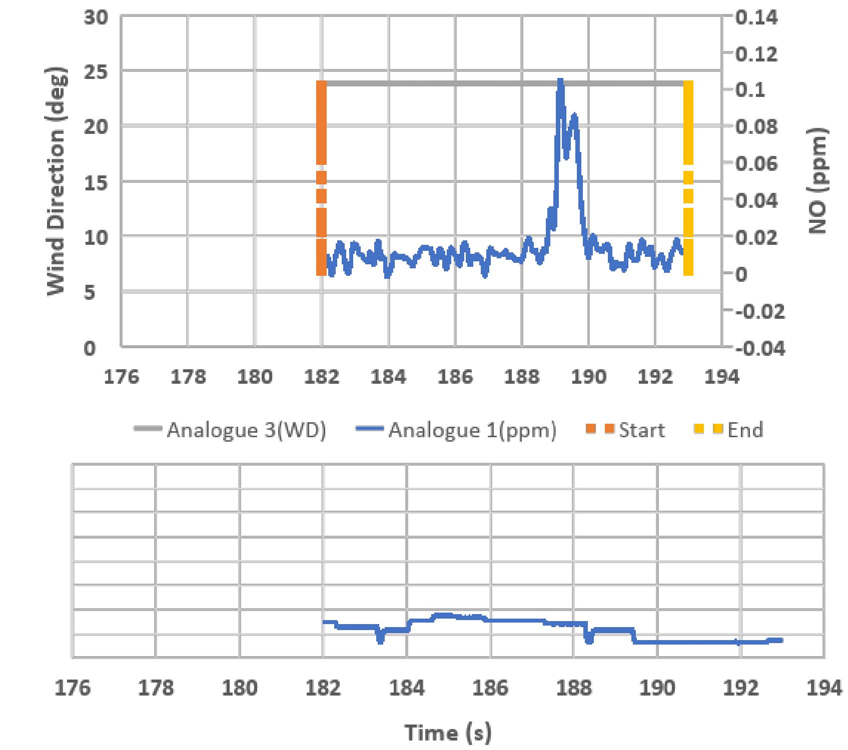


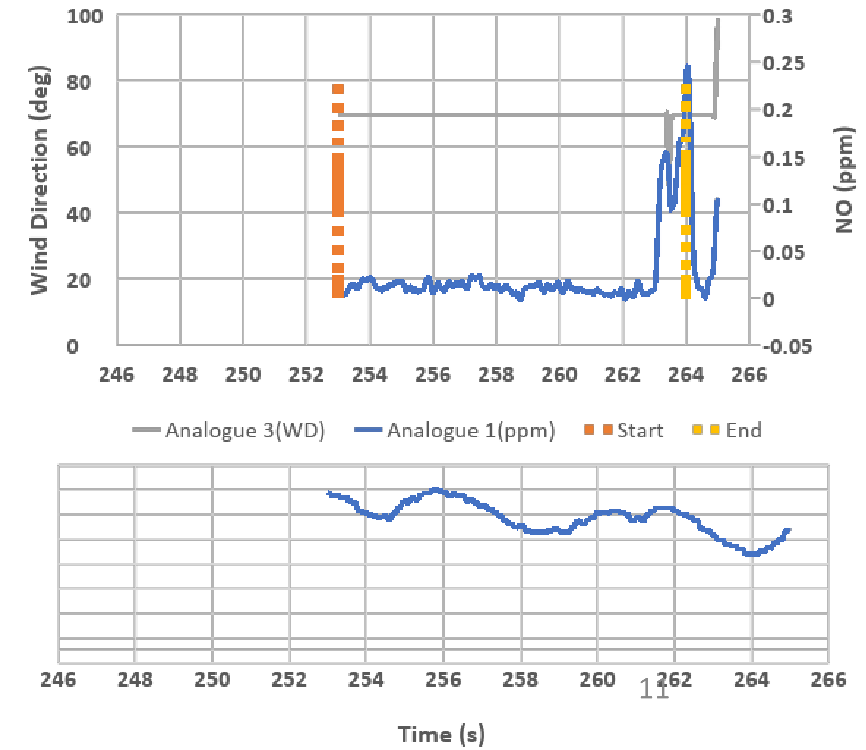
CFD Model Validation and Lessons Learned

- Due to the time constraints of the project, validation work has concentrated on the NOx recordings taken in Mansfield road (semi-open road configuration).
- While experience of use and available literature sources indicate that the OBU model predict gas dispersion accurately, direct validation was possible only under the following conditions: 1. Approximately constant wind direction; 2. Low wind speed (up to approximately 1.5 m/s); 3. Low wind speed variation.
- Three Mansfield Rd measurements satisfying the above conditions have been selected to show validation.

Run8 Go4- Height 1.3m, Mansfield Bottom of the Road	Run14 Go3- Height 1.7m, Mansfield Top of the Road	Run11 Go3- Height 1.3m, Mansfield Middle of the Road







CFD Model Validation and Lessons Learned

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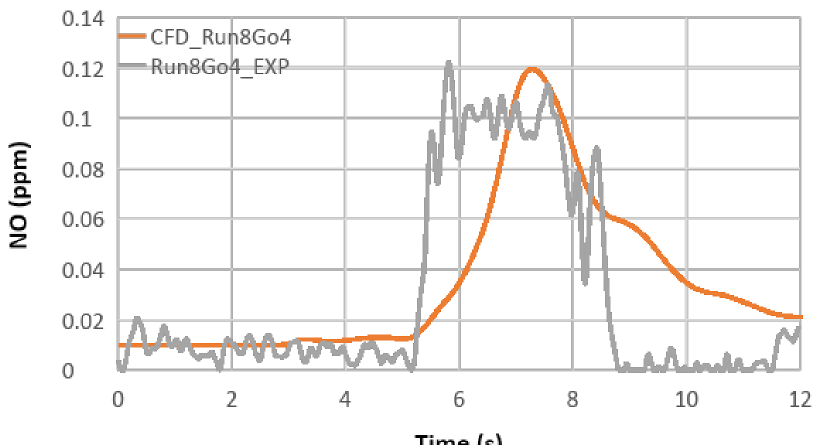
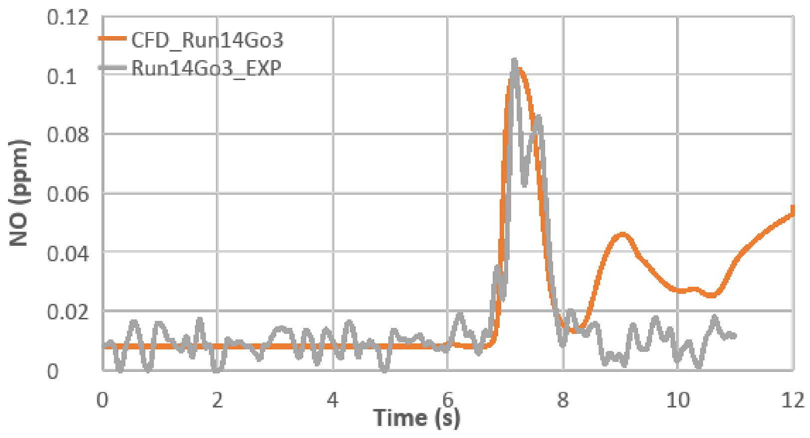
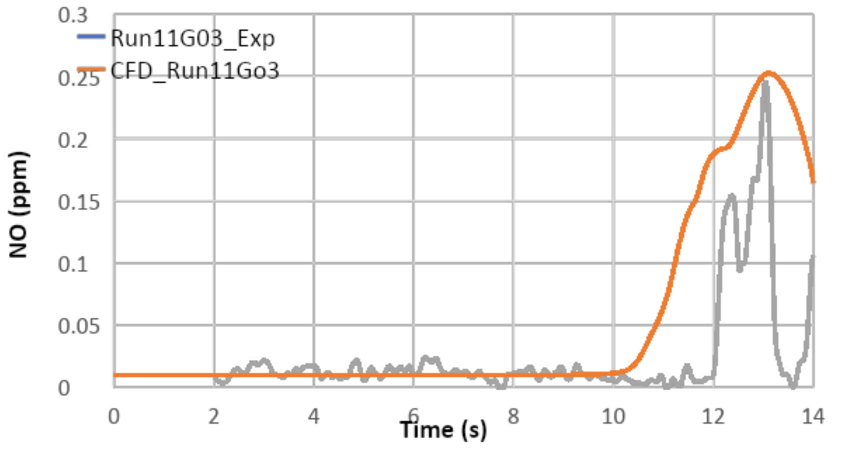




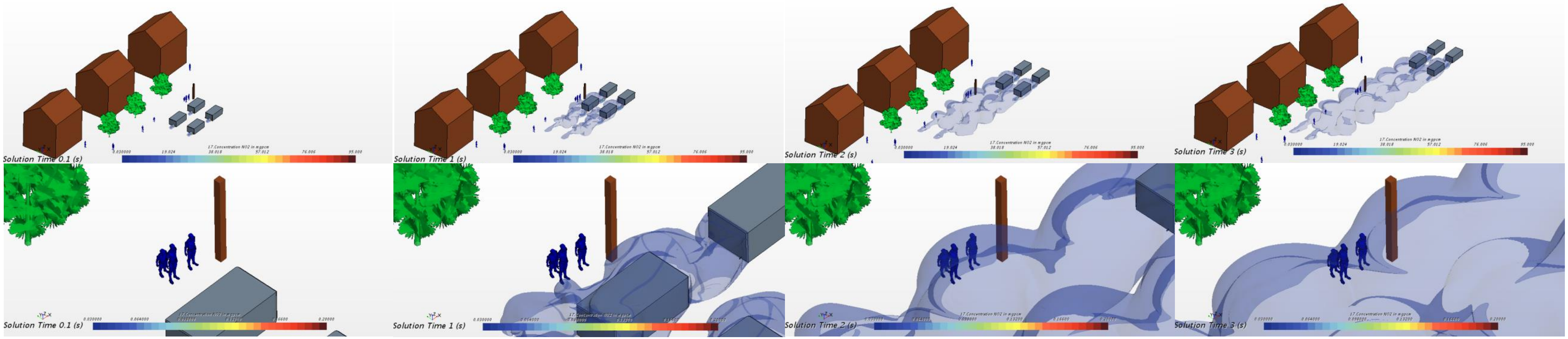


- Within the above constrains, and considering the complexity of the dynamic modelling exercise, the results show good matching of experimental and modelled road-side NO levels – both in terms of time alignment and magnitude.
    - This confirms that the relatively simpler topography of semi-open streets (Mansfield Rd) allows to use locally measured low-speed low-variability wind data as boundary condition for the simulation.

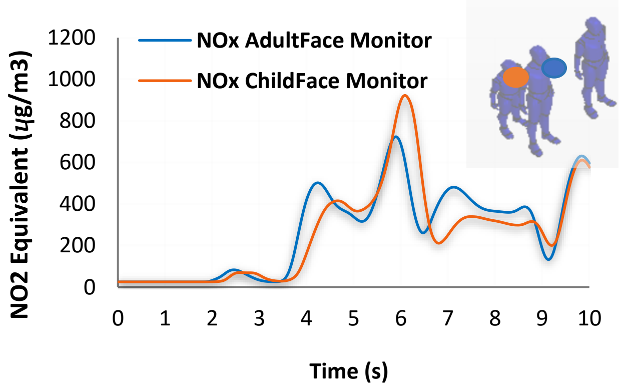
- In higher wind and wind variability cases, a carefully designed array of wind sensors, distributed locally but also at the boundaries of the modelled region (including high altitude free stream data) is necessary. This was beyond the scope and budget of this project.
- The authors estimate that the complexity of the road topography and fluid flow dynamics in the case of street canyons (Holywell Rd) also require a number of wind sensors.

General outline of the Momentary Exposure Phenomenon

- Depending on traffic levels and wind conditions, pedestrians (and cyclists) on the road side may be continuously exposed to high, repeating, momentary peaks of air pollution including NOx and PM from moving (or in fact stationary/queueing) traffic.
- The same phenomenon may also take place in other urban contexts such as bus and train stations.
- These peaks are not routinely measured by fixed monitoring stations and their effect on public health is not known or accounted for.

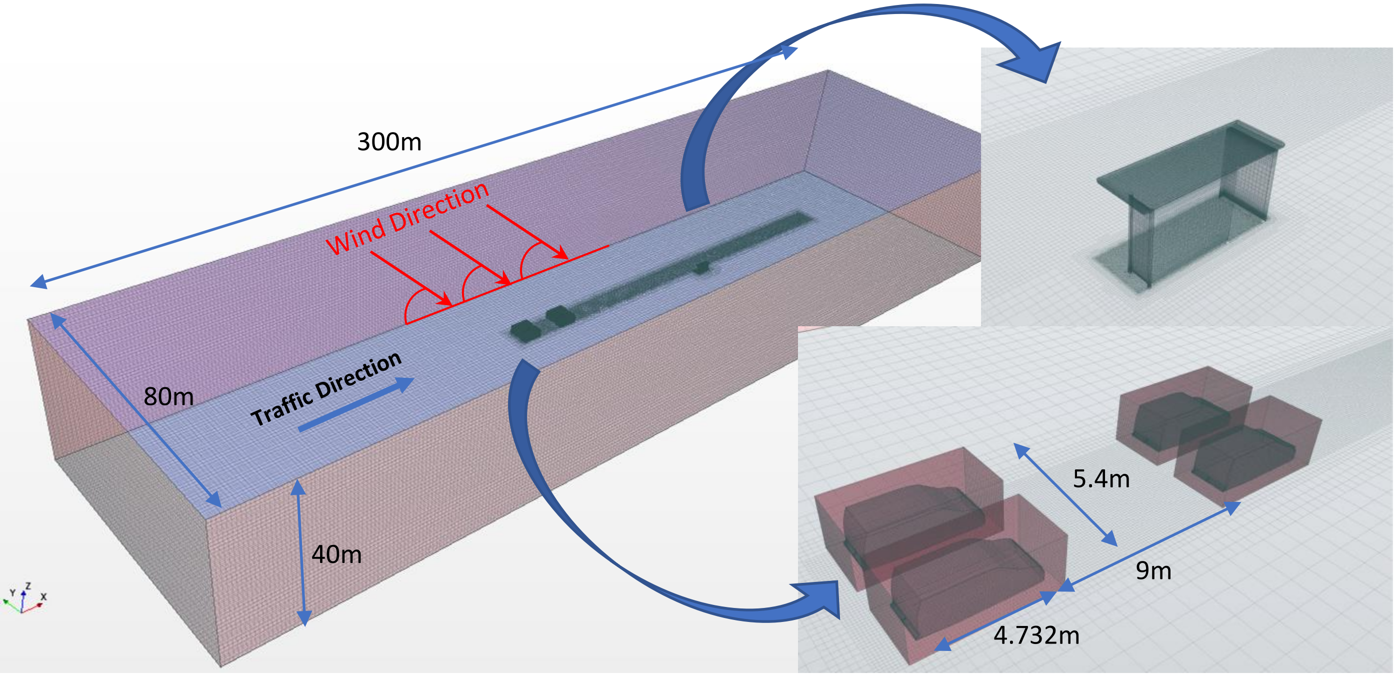


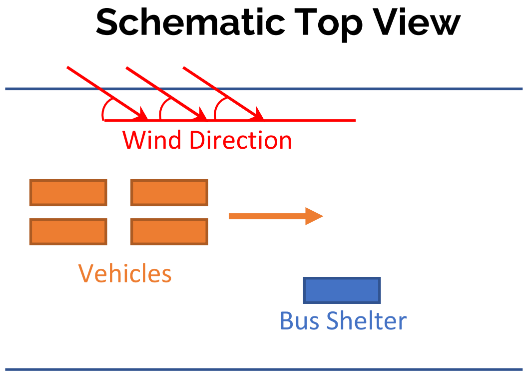
- The 10 sec generalised gas dispersion simulation reported here shows how gaseous NOx disperses towards a group of pedestrians and dissipates as the vehicles move away.
- With older vehicles on the road (Eu5 or older), the momentary NOx exposure levels may reach very high levels.
- Barriers or bus stop shelters may offer a level of protection against high momentary exposure.



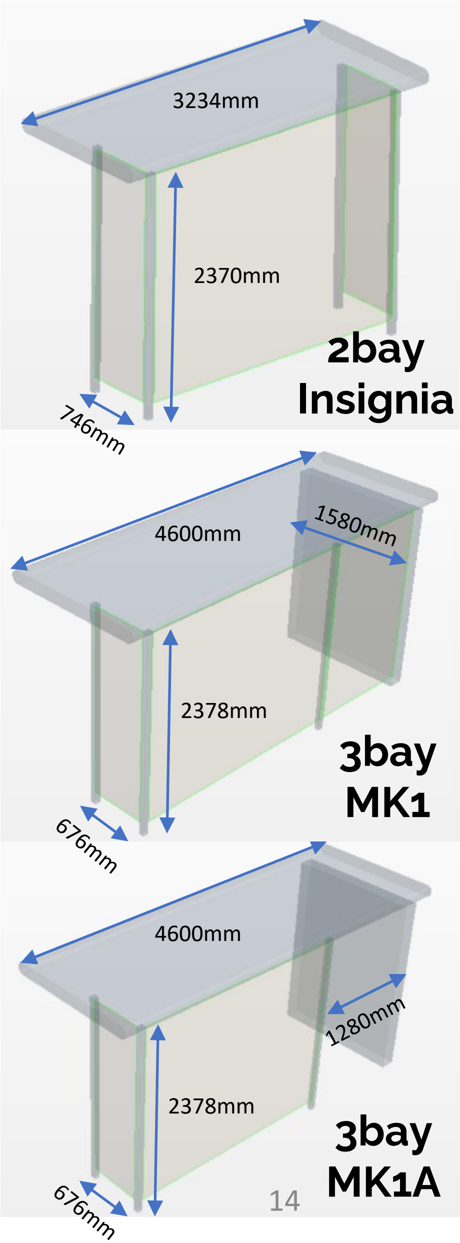
- Vehicles NO emission 0.04g/sec~ 1.67gr/m3 (Mid-to-high urban levels from EU5 vehicles)
- Constant speed vehicles, 32km/h
- Wind Speed of 5m/s (light breeze)
- Wind Direction 30˚ to the road, counterflow
- Background NO2 level of 28 μg/m3 (measured in Oxford)

Modelling Momentary Personal Exposure at Bus Stops





- A simplified open-road scenario was created for the purpose of modelling personal exposure at bus stops (and the protection shelters offer from exposure).
- A set of vehicles moves at constant speed along a 300 m stretch of straight road, while releasing a realistic amount of hot exhaust gases containing NO.
- For an enhanced comparative evaluation, each vehicle emits 0.04 gr/s of NO equivalent (based on a Real Driving Emissions (RDE) Eu5 Diesel Vehicle study by Costagliola et al., 2018).
- Three shelter designs by Clear Channel UK ltd, common in UK, are compared.
- The traffic direction in the model is compatible with the bus shelter original configuration, independently of left-hand or right-hand traffic systems.



Modelling Momentary Personal Exposure at Bus Stops

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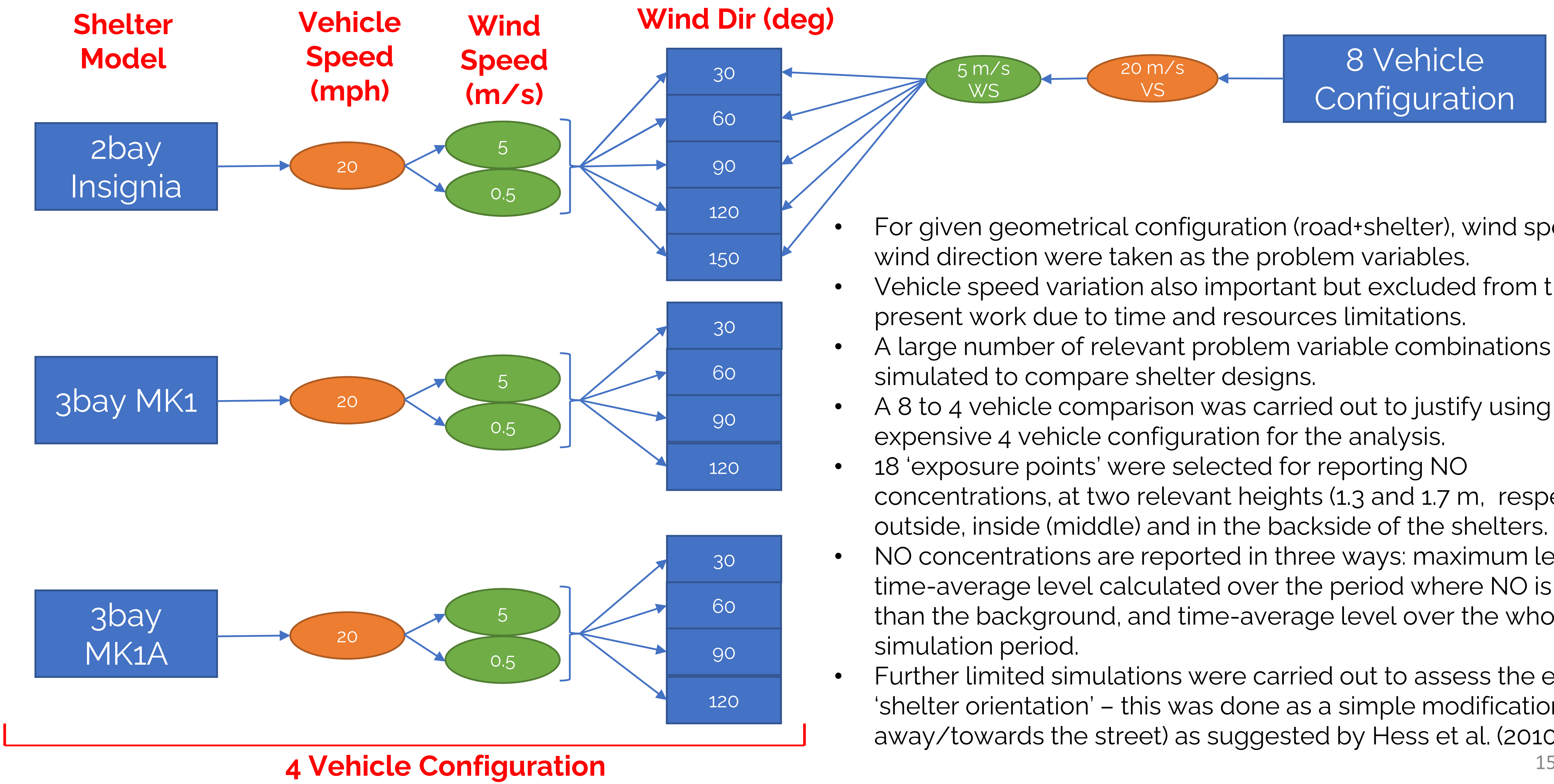
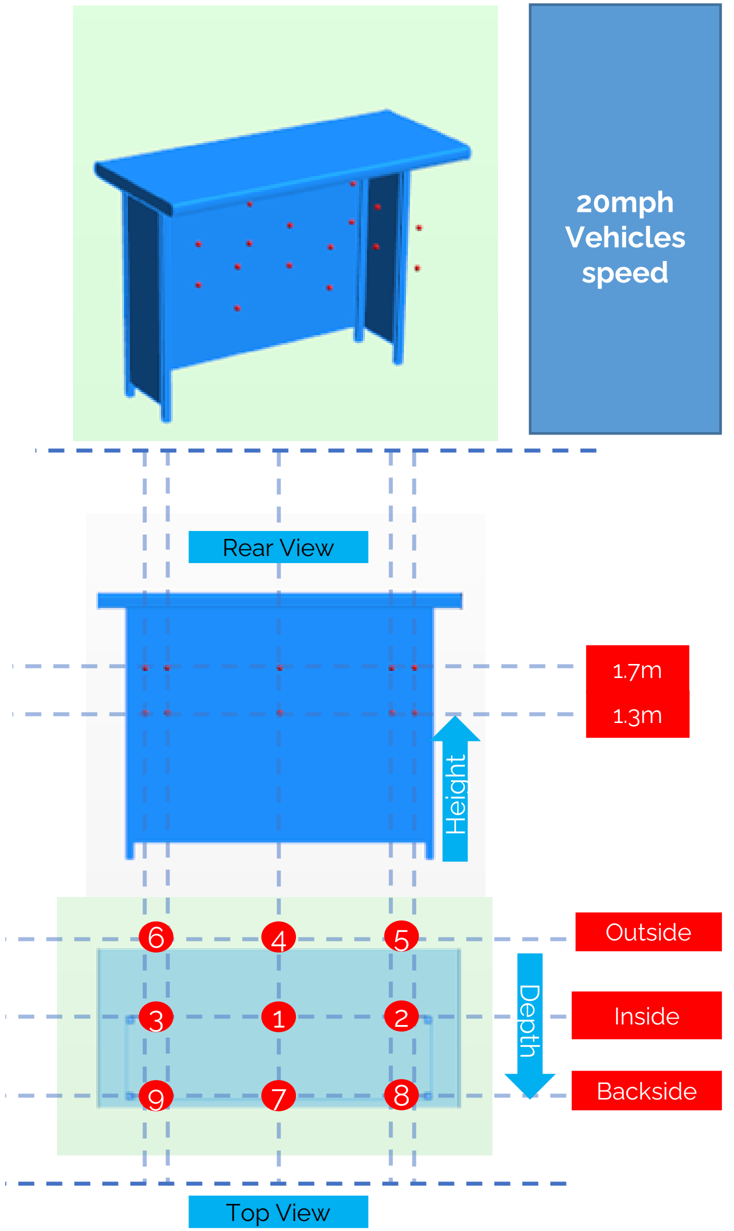


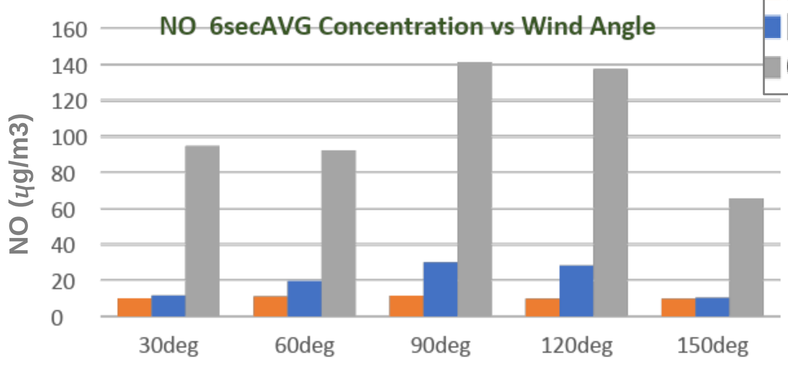
- For given geometrical configuration (road+shelter), wind speed and wind direction were taken as the problem variables.
- Vehicle speed variation also important but excluded from the present work due to time and resources limitations.
- A large number of relevant problem variable combinations were simulated to compare shelter designs.
- A 8 to 4 vehicle comparison was carried out to justify using the less expensive 4 vehicle configuration for the analysis.
- 18 'exposure points' were selected for reporting NO concentrations, at two relevant heights (1.3 and 1.7 m, respectively outside, inside (middle) and in the backside of the shelters.
- NO concentrations are reported in three ways: maximum levels, time-average level calculated over the period where NO is higher than the background, and time-average level over the whole simulation period.
- Further limited simulations were carried out to assess the effect of 'shelter orientation' – this was done as a simple modification (facing away/towards the street) as suggested by Hess et al. (2010).

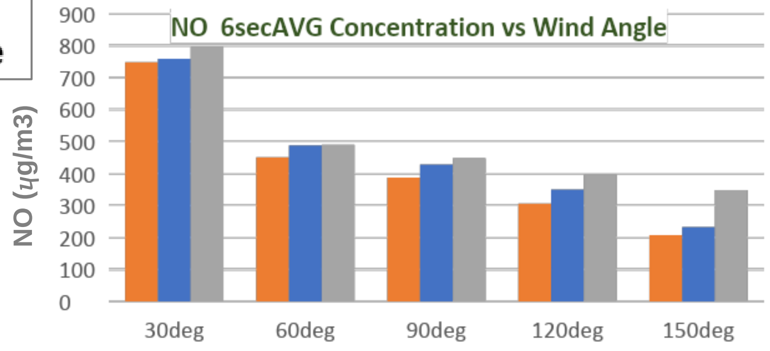
Results: 2-bay Insignia

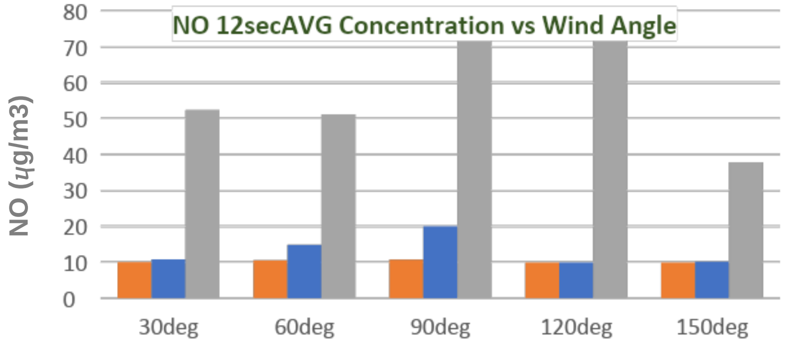


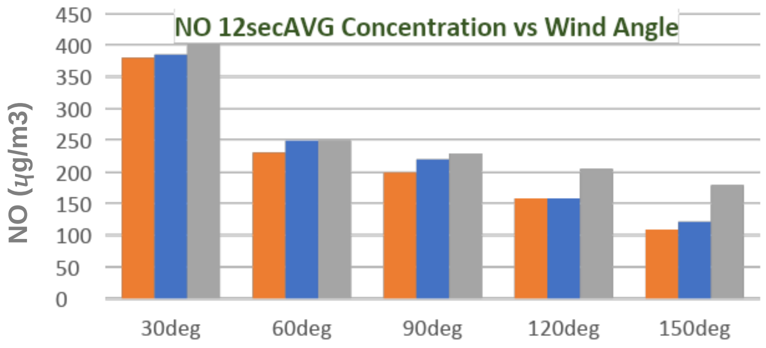
0.5m/s AVG variable Wind

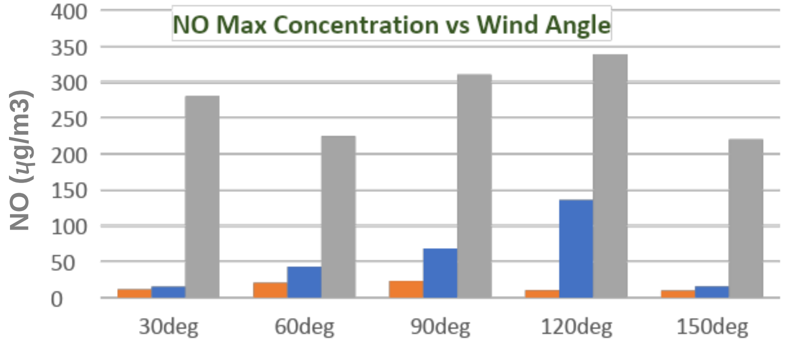
5m/s Wind

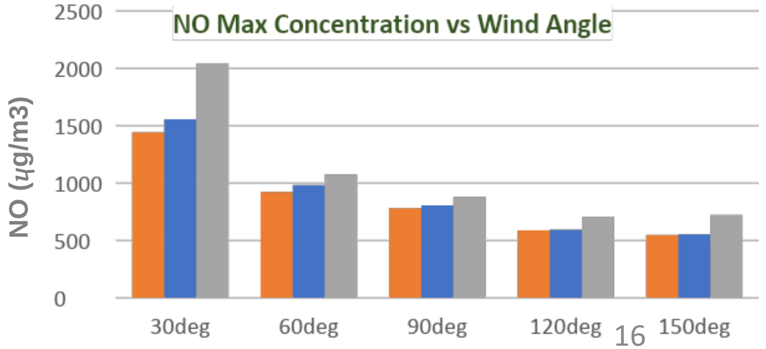












2-bay Insignia: Comparison of 4 and 8 Vehicle Configurations

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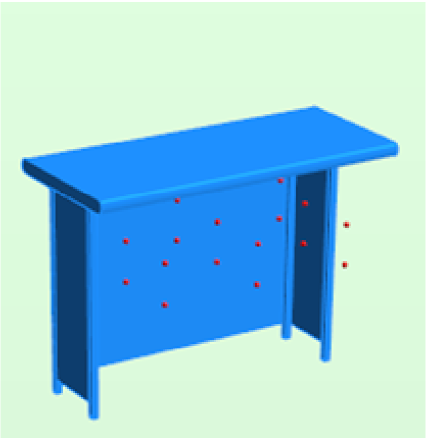
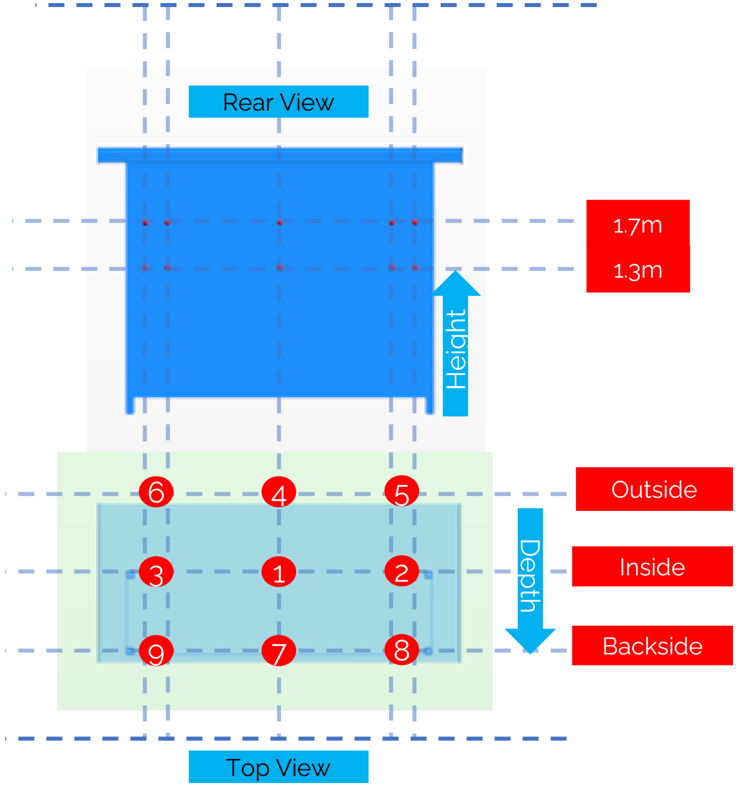
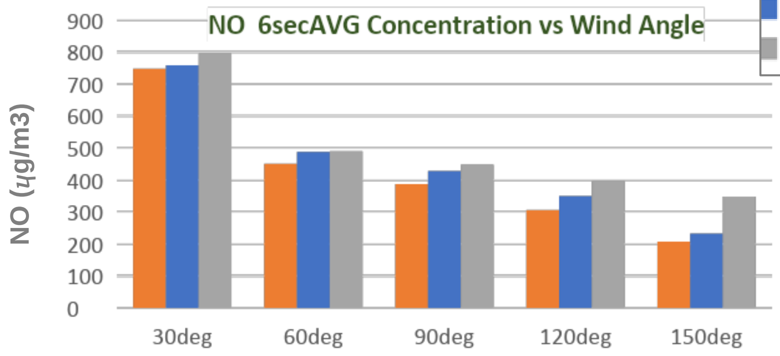


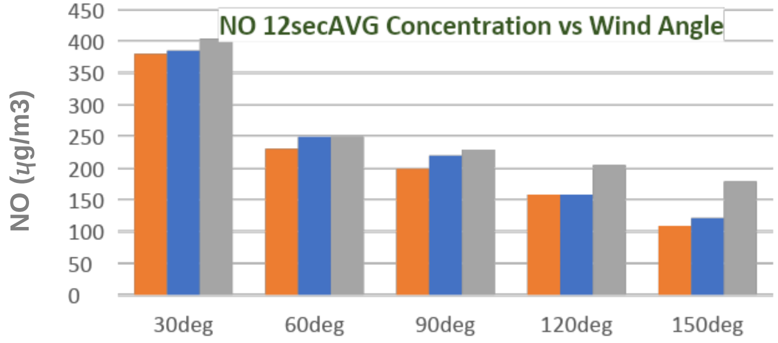
5m/s wind speed; 20mph Vehicles Speed

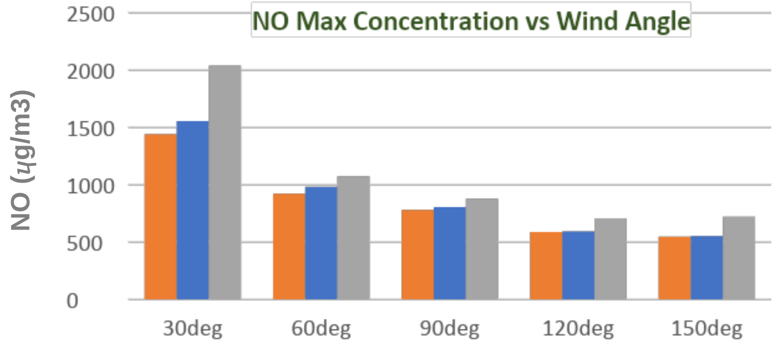


4 Vehicle

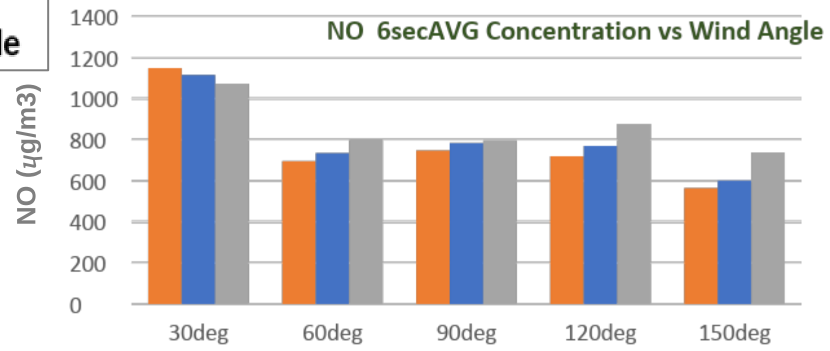
Backside
Inside
Outside

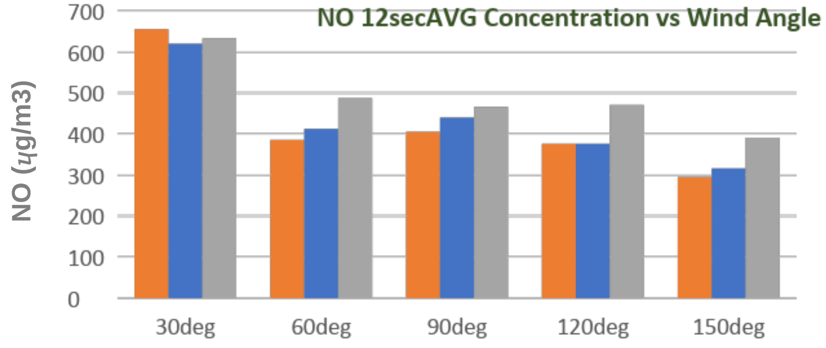


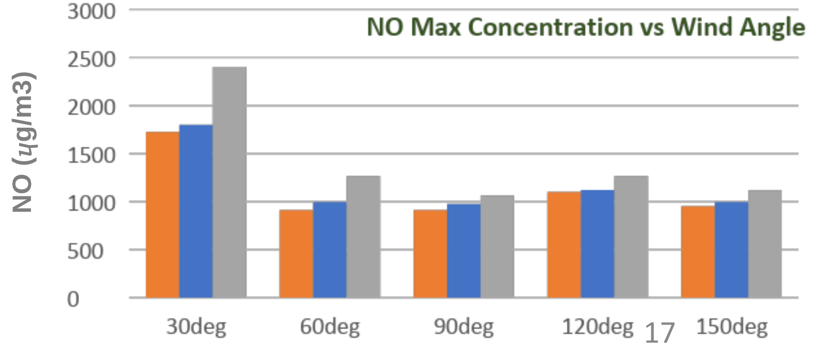




8 Vehicle





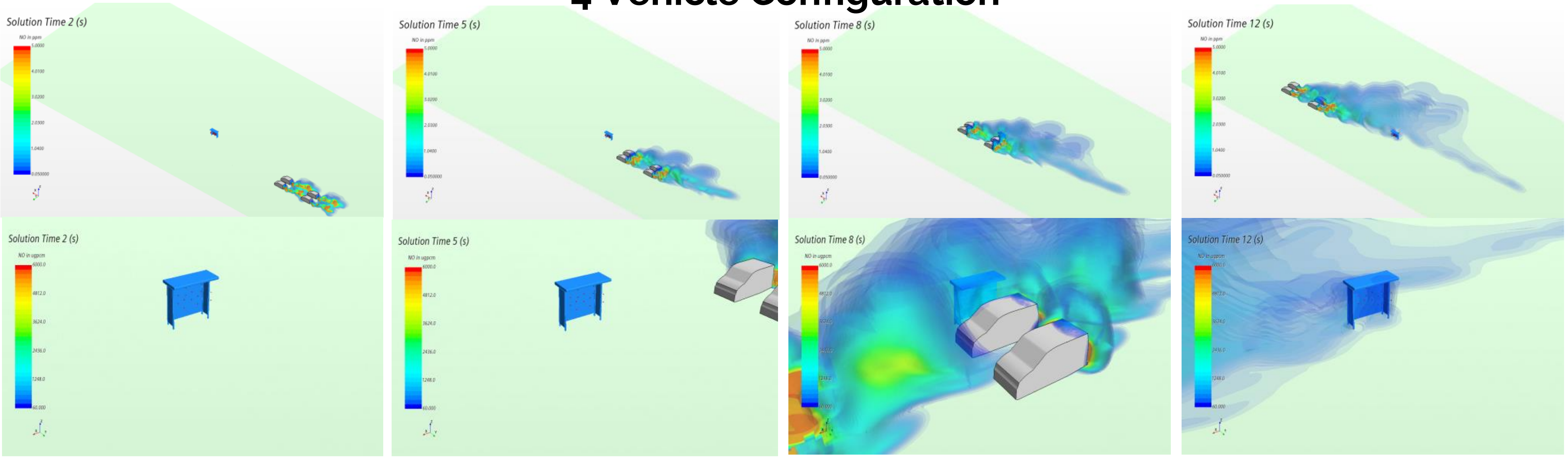


2-bay Insignia: Comparison of 4 and 8 Vehicle Configurations

4 Vehicle Configuration

Wide View

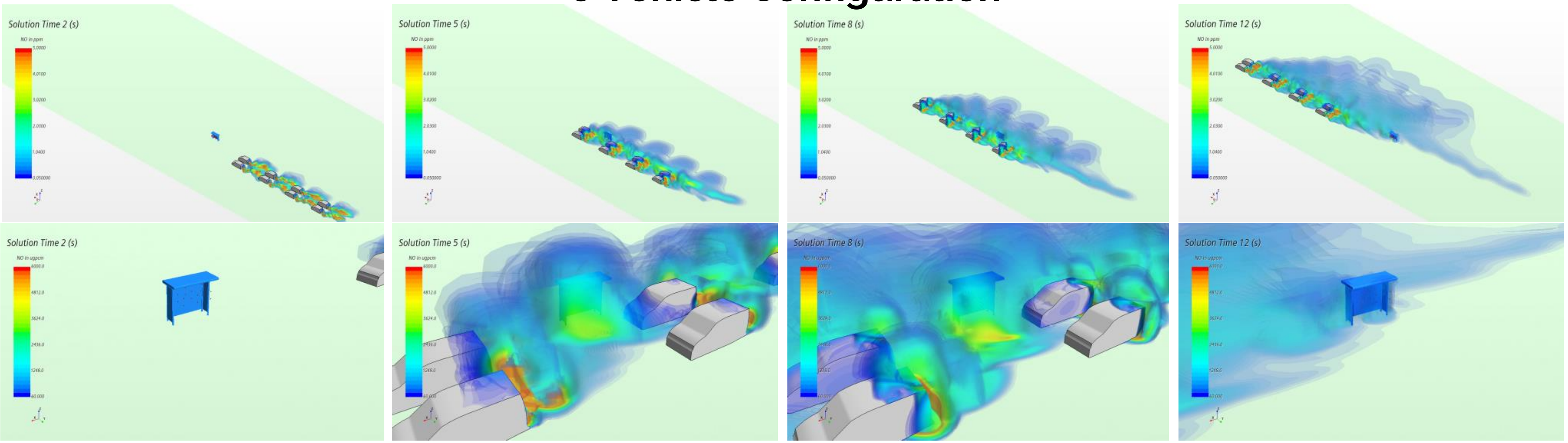
Zoom In



8 Vehicle Configuration

Wide View

Zoom In



5 m/s wind speed

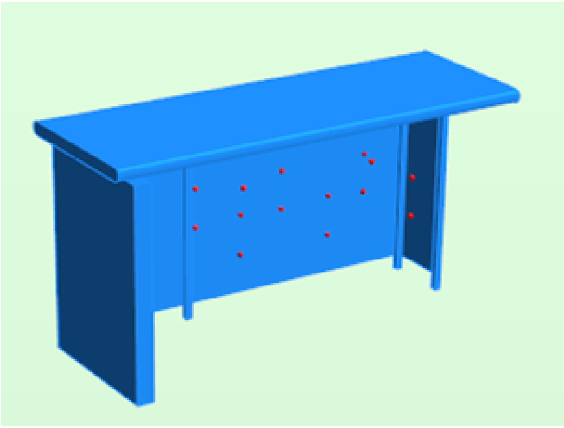
20 mph Vehicle Speed

30 Deg Wind Direction

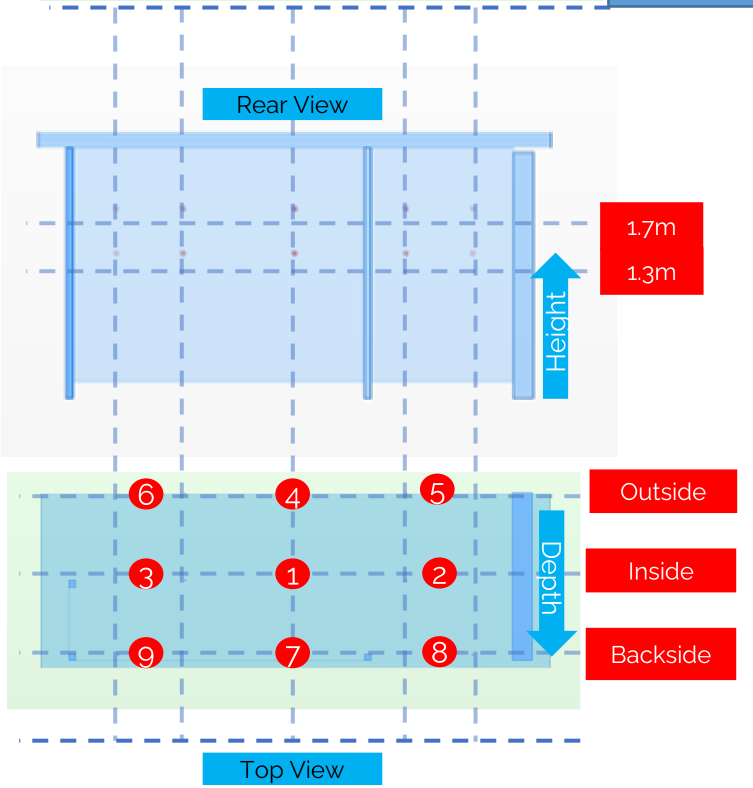
2-bay Insignia: Remarks

- For the low wind speed case (0.5 m/s), the highest 6sec average NO concentration of 140 ug/m3 is measured outside the shelter for a wind direction around the 90 deg mark. The levels inside the shelter are much lower (up to 90% lower), ie in this case the shelter offers protection from exposure.
- At low wind speed, wind direction between 60 and 120 deg causes the highest level of NO concentration and exposure at bus shelters.
- For the higher wind speed case (5 m/s), the highest 6sec average NO concentration of 800 ug/m3 is measured outside the shelter for a wind direction of approximately 30 deg. The levels inside the shelter are very similar, ie in this case the shelter does not offer protection from exposure.
- 5 m/s wind speed is the annual average level of wind speed across the UK. It is plausible to assume that higher wind speed may worsen the level of momentary personal exposure for pedestrian at bus stops.
- More vehicles on the road cause increased momentary exposure. A 8 Vehicle configuration generates increases of the measured 6sec average NO concentration of between 50 and 120%, depending on the wind direction.
- However, the comparison between the 8 Vehicle and 4 Vehicle configurations showed consistent effect of wind direction on exposure results. This justifies using the less computationally expensive 4 Vehicle configuration for the study.
- Cases of wind direction of 150 deg have consistently demonstrated lower levels of NO exposure. For this reason, 150 deg Wind Direction has been discarded from the rest of the study to minimise the cost of the CFD modelling.

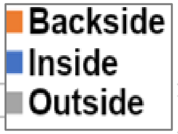
Results: 3-bay MK1

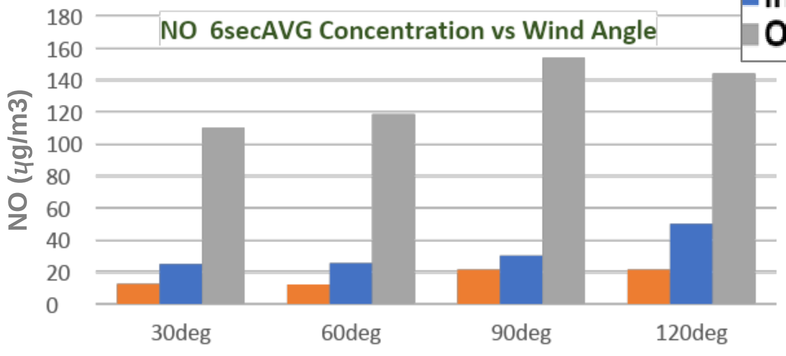


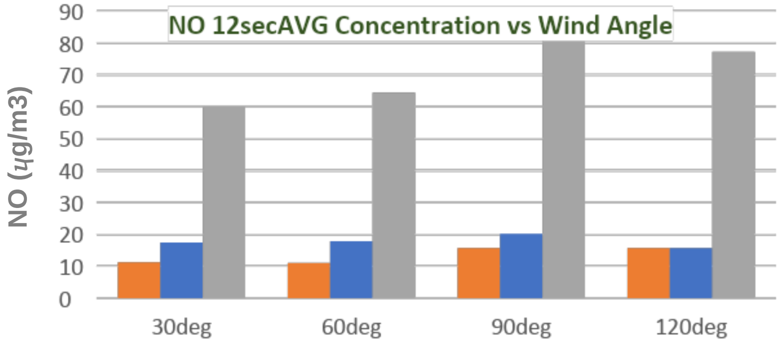
20mph Vehicles Speed

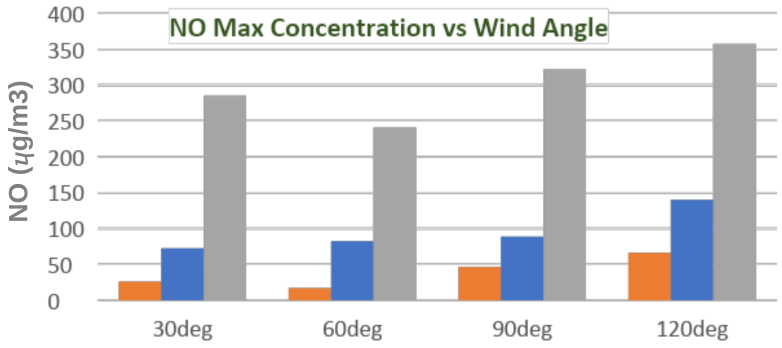


0.5m/s AVG variable Wind

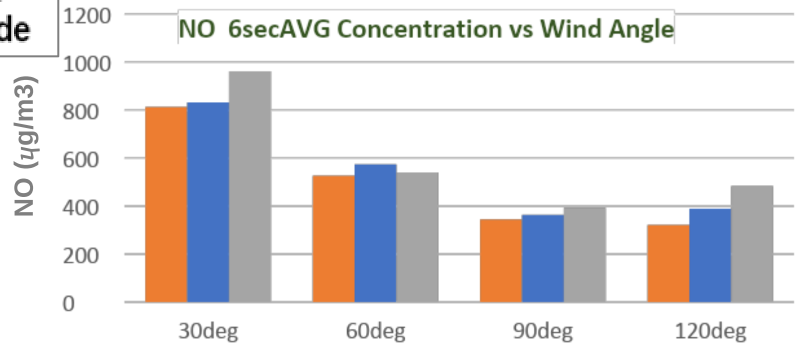


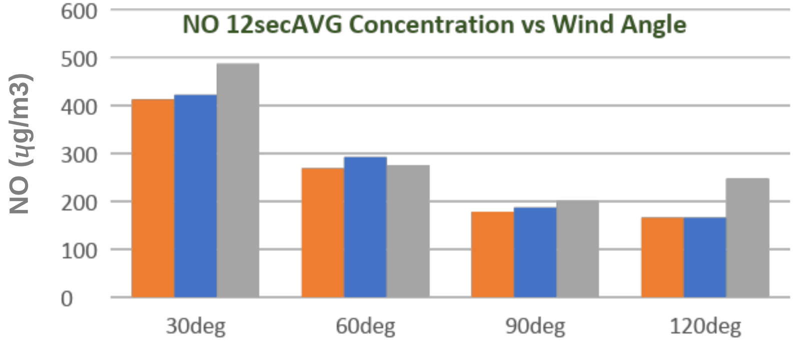


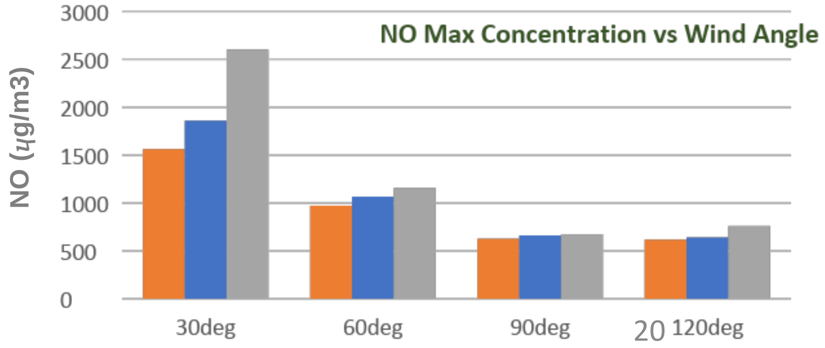




5m/s Wind







Results: 3-bay MK1A

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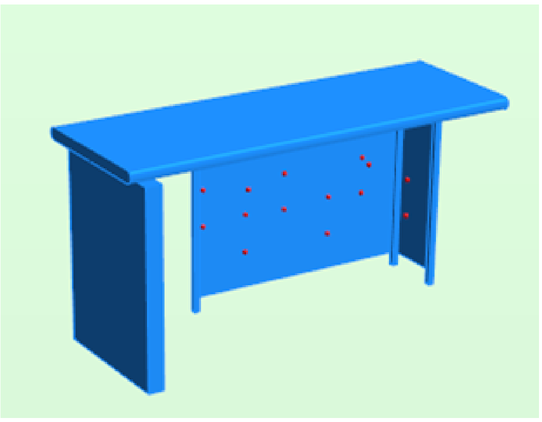
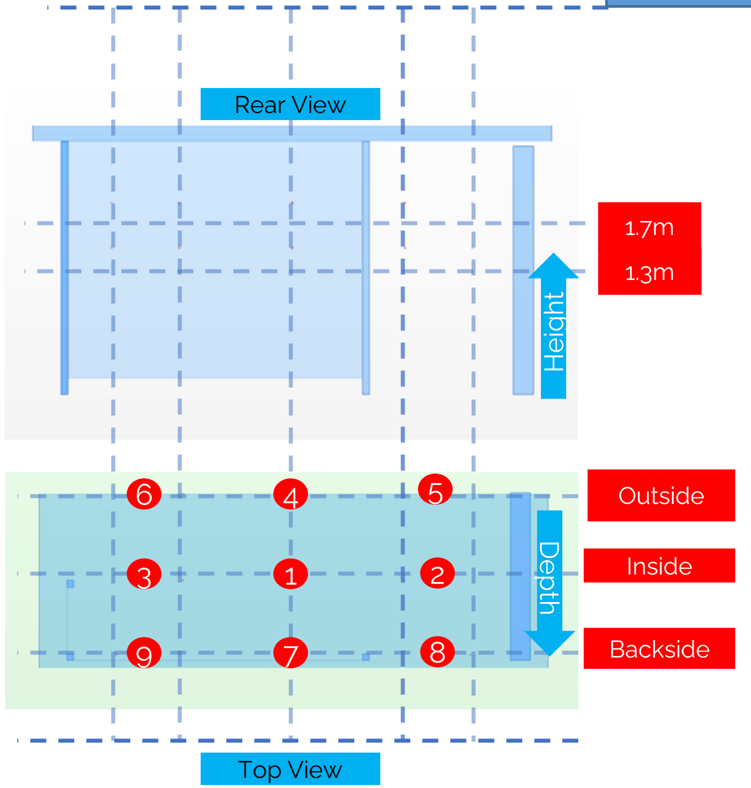
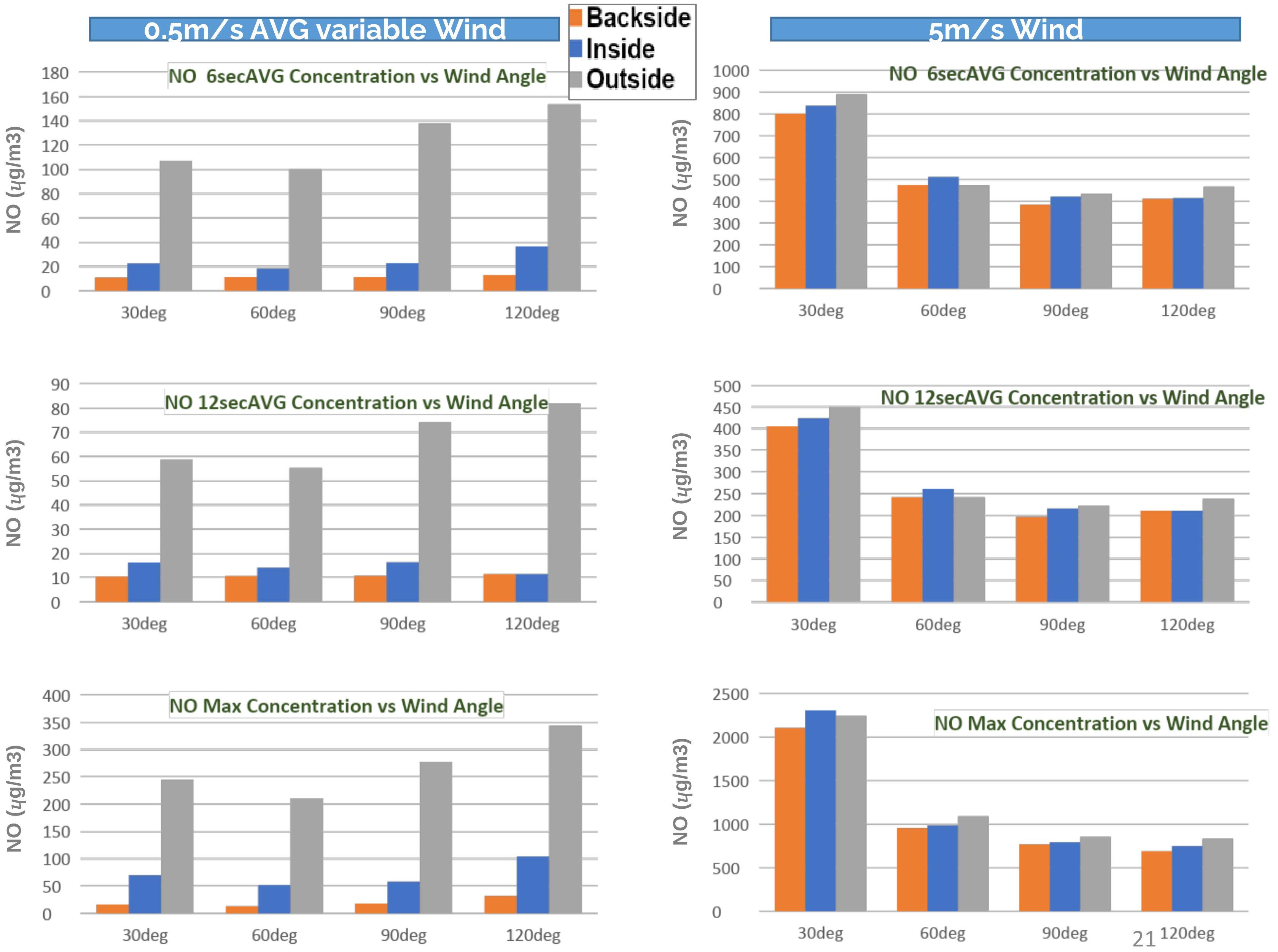


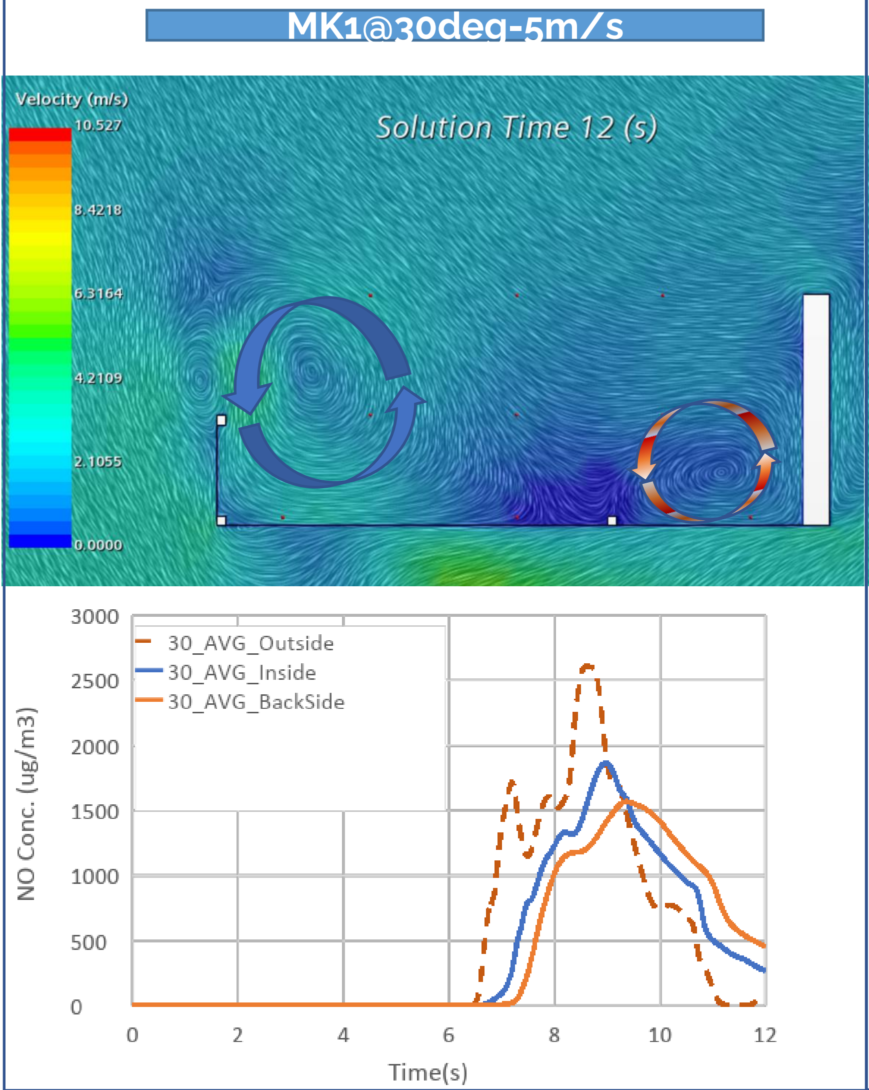
20mph Vehicles Speed

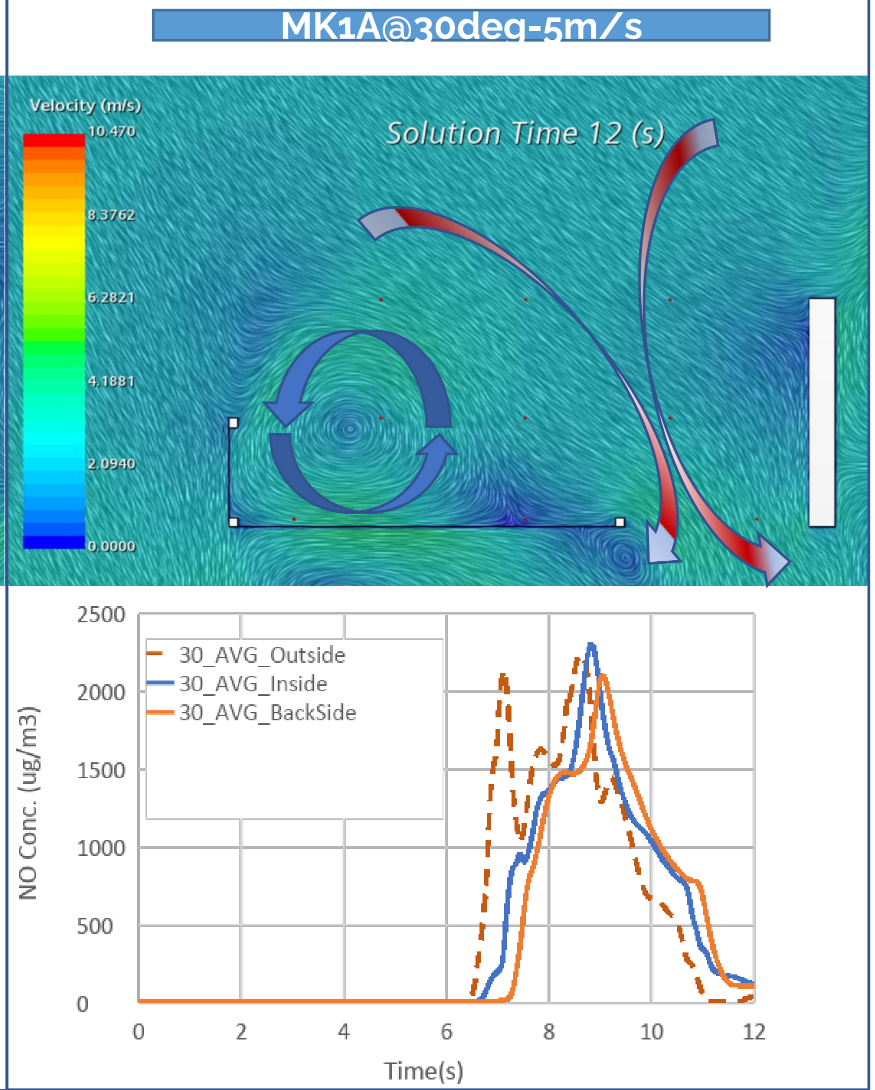


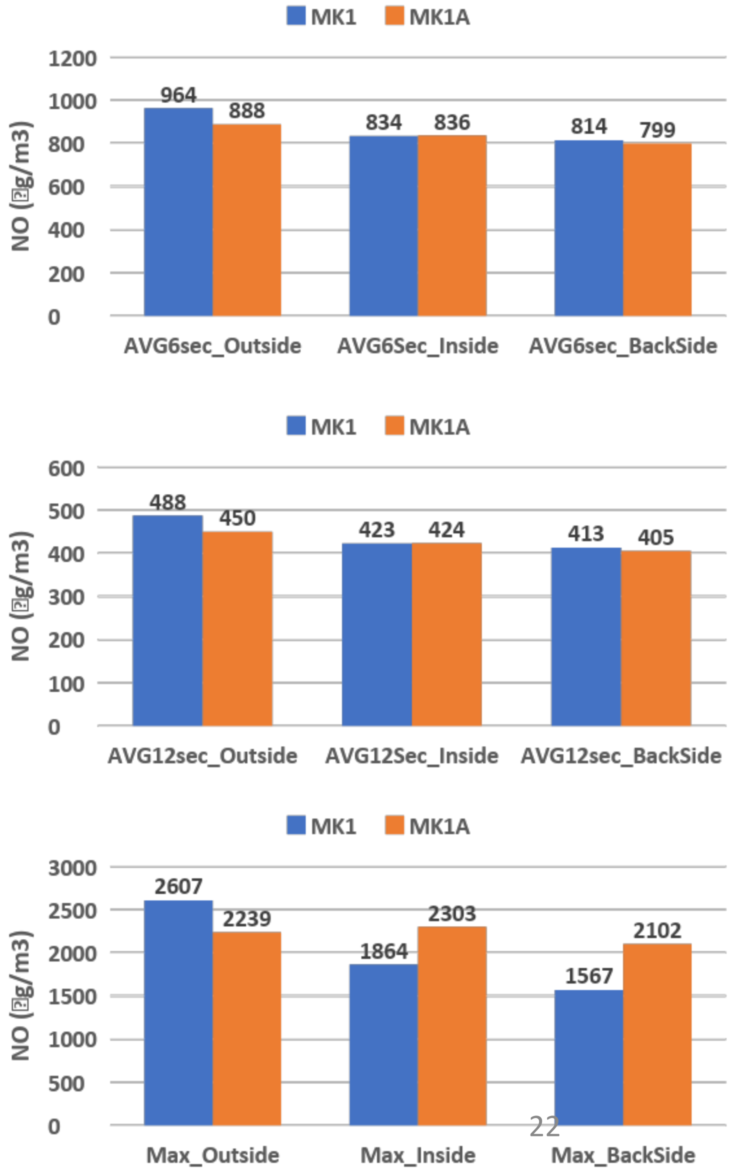


MK1 and MK1A Comparison

Top-view visualisation of airflow (velocity) and time-resolved NO concentrations inside and around the bus shelters







3-bay MK1 and MK1A: Remarks

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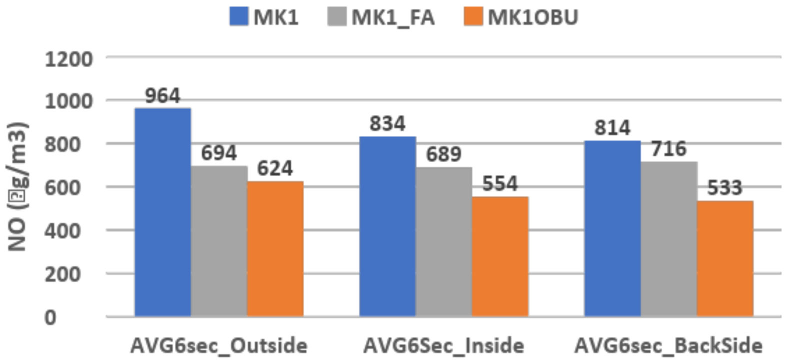
- In the case of low wind speed (0.5 m/s), both shelters designs provide a significant level of protection from exposure when people are inside/under the shelter.
- In low wind conditions, the highest 6sec average NO concentration of 154 ug/m3 is measured outside the shelter for a wind direction of 90 and 120 deg, for the MK1 and MK1A design respectively. The NO levels inside the shelters are up to 90% and 93% lower.
- As seen for the 2bay Insignia design, also the MK1 and MK1A designs offer reduced exposure protection under the UK average wind speed conditions of 5 m/s. The highest 6sec average NO concentrations of 964 ug/m3 and 888 ug/m3 are measured outside the shelter for a wind direction of 30 deg, for the MK1 and MK1A design respectively. Being inside the shelter enables 15% to 10% reduced exposure.
- The average levels of NO concentration outside of the shelter are generally measured to be higher for the MK1 design. The rear aperture of MK1A allows an airflow through the shelter resulting in slightly lower average NO concentrations also in the backside of the shelter. No measurable difference is seen in the inside (middle) section between the two shelter designs.
- The complex flow regime which establishes in the MK1A design causes much higher maximum NO concentrations in the inside (middle) and backside locations, compared to the MK1 design. The highest level of 2300 ug/m3 is measured in the inside section of MK1A, about 24% higher than MK1.

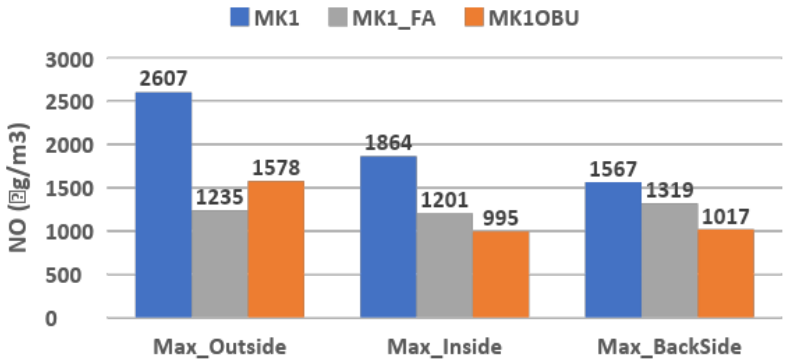
MK1 ‘Facing Towards’ vs MK1 ‘Facing Away’ vs New Design (MK1OBU)

- ‘Facing away’ (from the street) shelters orientation offers, as expected, increased level of personal protection from exposure to air pollution.
- Simulations carried out to quantify the enhanced protection, referring (as an example) to the MK1 design.
- Speculative facing away design (MK1OBU) also considered for comparison.
- Worst case atmospheric conditions of 30 deg WD and 5 m/s WS.
- The results show that simple modifications, where feasible, can actually improve the air quality both in and around the bus shelter.

Percent reduction in 6-sec average NO concentrations, compared to original 3bay MK1 ‘Facing Towards’ configuration

Shelter Design/Config.	Outside	Inside	Backside
MK1 Facing Away	28%	17%	12%
MK1OBU (Facing Away)	35%	34%	35%





MK1OBU

- 3bay design with single rear access
- Orientation Facing Away from traffic
- Side width doubled up from 0.625m to 1.25m
- Vents designed for natural ventilation at the top with 0.15m openings.

General Conclusions

- Both steady and queuing (start-stop) traffic would produce large (momentary but repeating) peaks of air pollution on the road side – the public (e.g. people at bus stops) is continuously exposed to peaks but routine road-side stations cannot measure them.
- High-resolution 3D CFD modelling can be used to describe the phenomenon and assess the impact of mitigation strategies – the OBU model was validated against road-side NO measurements and used to assess personal exposure in and around bus stop shelters.
- Direct validation was possible only under approximately constant wind direction, low wind speed (up to 1.5 m/s) and low wind speed variation; In stronger, highly variable winds, a carefully designed array of wind sensors is necessary (including high altitude free stream data). This was beyond the scope and budget of this project.
- In gentle breeze conditions (5 m/s), a set of four Euro 5 diesel vehicles may generate road-side peaks of equivalent NO concentration as high as 2600 ug/m3, with 6-second average levels of 800 ug/m3.
- Bus stop shelters facing towards the road offer good protection from exposure (up to 90% NO reduction) only in low wind conditions; in gentle breeze, being inside the shelter offers minimal protection (up to 15% NO reduction).
- Shelters in ‘facing away’ orientation offer improved protection (up to 20% compared to facing towards orientation) and simple design modifications may further reduce the potential exposure.
- More vehicles cause consistent but greater road-side NO concentrations and hence exposure; a 8-vehicle configuration generates increases of average NO levels between 50 and 120%, depending on the wind direction.

Link to publicly accessible data (CEDA)

The experimental 'field-test' data collected for model validation, along with a short document to aid its interpretation, is publicly available at the following link:

http://dx.doi.org/10.5285/53a1acaf5adb4b22b19397bf08d229ef