



PALM-Traffic 2.0: Implementation of the traffic-induced heat and velocity in the PALM model system

Jaroslav Resler^{*1}, Michal Belda², Martin Bureš¹, Kryštof Eben¹, Vladimír Fuka², Jan Geletič^{1,2}, Josef Keder³, Pavel Krč¹, Veronika Květoňová¹, Tereza Pikousová³, Jelena Radović², Hynek Řezníček¹, Petra Tesařová³, and Ondřej Vlček³

¹Institute of Computer Science, Czech Academy of Sciences, Pod Vodárenskou věží 271/2, 182 00 Prague 8, Czech Republic

²Department of Atmospheric Physics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00, Prague 8, Czech Republic

³Czech Hydrometeorological Institute, Na Šabatce 2050/17, 143 00 Prague 12, Czech Republic

Correspondence: Jaroslav Resler* (resler@cs.cas.cz)

Abstract. The new Traffic model has been developed and integrated into the PALM model system 26.10. Using data typically available for traffic emission modelling, it adds the parameterised impacts of car-induced heat and air flow on modelled tendencies of potential temperature and advection. Model evaluation in a realistic urban environment showed a significant impact of the traffic model at 1 m resolution on street canyon turbulent flow: it changes the wind component aligned with the street canyon by about 2.0 m s^{-1} and turbulent kinetic energy by about $0.6 \text{ m}^2 \text{ s}^{-2}$. The increase of potential temperature was the strongest during stable stratification at night and early morning by up to 1.5 K; after the start of convection there was a modest increase of $\approx 0.5 \text{ K}$. The 4 m resolution domain showed a lower impact. Comparison with measurements obtained in a dedicated observation campaign in two parallel streets with heavy traffic showed that applying the model typically brings simulated results closer to observations, with good agreement between modelled and observed values. Comparison of the horizontal turbulent spectra showed that applying the Traffic model brings modelled spectra very close to those calculated from observations, with the impact at all frequencies including high frequencies close to the observation and model time resolution 1 Hz. The impact on air quality was tested in a simulation replicating a previously published study of a stable, low-wind winter situation. The results showed that the Traffic model significantly affected PM_{10} concentrations, changing both their magnitude and spatial distribution and substantially reducing the instabilities found in simulations without traffic effects. It demonstrated that inclusion of the transportation-produced momentum and heat forcing in the model is necessary for reliable realistic simulations of the stable low wind meteorological conditions.

1 Introduction

On-road traffic flow is a major contributor to atmospheric contamination and air quality degradation in urbanised regions, due to its continuous and highly concentrated emissions of air pollutants (e.g., particulate matter–PM, nitrogen oxides– NO_x , carbon monoxide–CO, volatile organic compounds–VOCs; Zhang and Batterman, 2013). Driven by rapid urbanisation, rising traffic volumes and persistent traffic congestion, these emissions intensify pollutant accumulation at the pedestrian level and



in their breathing zone. This effect is especially pronounced in street canyons, where the surrounding urban morphology inhibits vertical turbulent exchange, ventilation, and advective transport (Oke et al., 2017). The adverse health effects linked to traffic-induced increases in air pollutant levels, including respiratory infections and illnesses such as asthma, cardiovascular conditions, and metabolic and neurological risks are of great concern (World Health Organization, 2024; World Meteorological Organization, 2021). Hence, accurately resolving complex fluid dynamics and modelling street-level air pollutant transport and dispersion are fundamental prerequisites for high-precision urban atmospheric assessment, including quantifying pollutant exposure and designing mitigation strategies.

In addition to acting as sources of pollutants, vehicles alter ground-level atmospheric dynamics by introducing momentum, turbulence and heat, which in turn alter airflow patterns, thermal stability, and consequently the dispersion of pollutants within street canyons (see e.g., Kastner-Klein and Plate, 1999; Baik and Kim, 1999; Chang and Meroney, 2003; So et al., 2005; Eliasson et al., 2006). Vehicle-induced heat (VIH) can significantly influence temperature and, indirectly, thermal stability and ventilation in the street canyon under stable meteorological conditions (Resler et al., 2024).

The direct influence of airflow from a car follows from the fact that each moving vehicle acts as a bluff body immersed in the street-canyon airflow, disturbing the surrounding air through two coupled mechanisms: vehicle-induced momentum (VIM) and vehicle-induced turbulence (VIT). These vehicle-driven processes become especially important under stable atmospheric conditions (i.e., temperature inversion, suppressed vertical motion, weak winds), when vertical turbulent exchange is inhibited and, as a result, vehicle-generated mixing and turbulent exchange emerge as dominant drivers and mechanisms of scalar transport across the street-level canopy (Cai et al., 2020).

The VIM and VIT, as physical phenomena, have been extensively investigated, and their importance has been established in the scientific literature through wind-tunnel experiments, field measurements, and high-resolution numerical simulations. For instance, on-road measurements conducted along highways and in densely built urban settings reveal that passing vehicles increase turbulence intensity, cause pronounced modifications to the near-surface flow field, and enhance both vertical and horizontal mixing of pollutants in the vehicle-induced wake region (DePaul and Sheih, 1986; Qin and Kot, 1993; Alonso-Estébanez et al., 2012; Miller et al., 2019; Miller, 2022; Hu and Noll, 2023). Alongside field studies, wind-tunnel experiments have been used to further quantify the effects of moving vehicles on wake formation and dynamics, street-canyon flow and circulation patterns, and the dispersion of vehicle exhaust gases under controlled laboratory conditions (Kastner-Klein et al., 2000b, 2001; Baker and Hargreaves, 2001; Kanda et al., 2006a, b; Gromke and Ruck, 2007; Carpentieri et al., 2012).

Numerous computational frameworks have been developed to include the effects of moving vehicles in different kinds of atmospheric dispersion models or in complex flow and turbulence models. The most straightforward methods involve parameterising traffic-induced wake effects by modifying the Gaussian plume parameters or introducing additional turbulent diffusion (Kastner-Klein et al., 2000a; Jícha et al., 2000; Jícha and Pospíšil, 2002; Di Sabatino et al., 2003; Kastner-Klein et al., 2003; Solazzo et al., 2007; Sahlodin et al., 2007) or by additional turbulent kinetic energy (TKE) production terms in RANS-based CFD (Thaker and Gokhale, 2016; Pospíšil and Jícha, 2017, 2019). Although computationally efficient, these parameterisations fail to explicitly resolve and model vehicle-induced flow obstruction or localised wake structures.



In contrast, high-fidelity CFD approaches directly resolve the detailed flow field around individual vehicles, allowing explicit representation of the unsteady wakes they produce. Such approaches, using Reynolds-averaged Navier–Stokes equations (RANS) (Sahlodin et al., 2007; Wang and Zhang, 2012; Bhautmage and Gokhale, 2016; Kim et al., 2016; Lo and Kontis, 2017; Jin et al., 2017; Shi et al., 2019) and Large-eddy simulation (LES) (Li et al., 2017; Wang et al., 2019; Woodward et al., 2019; Cai et al., 2020; Zhang et al., 2017, 2024; Hashad et al., 2022), are used to explicitly simulate turbulence and momentum dynamics generated by vehicles. However, the substantial computational cost limits the applicability of the explicit approach to relatively small computational domains and short simulation periods.

In the case of distributed-source and quasi-steady formulations, the overall effect of traffic is accounted for by spatially distributed sources of momentum and turbulence rather than explicitly modelling each vehicle as an individual moving object (Jícha et al., 2000; Jícha and Pospíšil, 2002; Katolický and Jícha, 2005). Related approaches were used for LES simulations of street-canyon air-pollution dispersion by, e.g., Zheng and Yang (2021, 2022); Hashad et al. (2022).

Woodward et al. (2019) investigated the joint effect of moving vehicles and contaminant emissions varying in time based on the vehicle acceleration while explicitly including the moving vehicles as rectangular blocks in a large eddy simulation. Recently, Motisi et al. (2026) proposed and validated an imposed velocity method, a simplified form of the immersed boundary method, to include moving vehicles in the PALM model system.

The principal importance of these processes for microscale air quality modelling was also demonstrated in study Resler et al. (2024), and subsequent tests led us to develop the Traffic model for the PALM model system (Maronga et al., 2020). The main objective of this implementation is to parameterise the aerodynamic and thermal impacts of moving vehicle streams using information typically available in urban air-quality applications. The Traffic model computes additional momentum and potential temperature tendencies, which are then coupled directly to the atmospheric flow solver. This approach enables simulation of traffic-induced modifications of the local wind field and thermal environment, providing a more physically consistent representation of near-road atmospheric processes. As a result, this module enhances PALM’s capability to simulate urban microclimatic conditions, pedestrian thermal comfort, and air quality in traffic-affected urban environments, with the largest improvements expected during stable, low-wind situations where traffic-induced forcing becomes comparable to the background atmospheric mixing (Resler et al., 2024). The first implementation of this module was introduced in PALM version 25.10. In this study, we present Traffic model version 2.0, incorporated into PALM version 26.10, which introduces a substantially redesigned framework for representing traffic-induced momentum and heat fluxes. The new implementation improves the physical formulation and computational flexibility, thereby extending and enhancing PALM’s capacity to represent interactions between urban traffic and the atmospheric boundary layer with high fidelity. It also simplifies the input data requirements by direct utilisation of data commonly available and used for traffic emission modelling.

Section 2 describes the physics used in the model, and Section 3 shows basic principles of its implementation. The PALM model system with the new Traffic model was tested in a real case study in a traffic-burdened area of Prague. The impact of different configurations of the Traffic model was evaluated (Section 5.1), the model was validated against measurements collected in a dedicated field observation campaign (Section 4.5, 5.2), and the impact of the Traffic model on modelled air



90 quality was tested (Section 5.3). In Section 6, the uncertainties of the results (Section 6.1) and the limitations of the current version of the model (Section 6.2) are discussed.

2 Calculation of the car-induced forcing

The Traffic model calculates additional wind and potential temperature tendencies caused by moving vehicles. The goal of this model is to parameterise traffic flow based on traffic-line parameters and flow characteristics (i.e. not simulating in detail the
95 airflow around an individual car).

2.1 Calculation of the wind velocity tendency induced by cars

The magnitude of the drag force F_d of the moving car is given by the standard formula (see, e.g., Nath et al., 2021):

$$F_d = 0.5 C_d S_{\text{car}} \rho_{\text{air}} r^2, \quad (1)$$

where C_d [1] stays for the aerodynamic drag coefficient, ρ_{air} [kg m^{-3}] is air density, and r [m s^{-1}] represents the relative car
100 speed against air. The S_{car} [m^2] means the area of the car projected in the direction of the relative car velocity vector $\mathbf{r}$.

The drag force is calculated in the vehicle-fixed coordinate system with axes perpendicular to the front, side, and top faces of the car. The components of $\mathbf{r}$ in the car coordinate system will be denoted as r_f , r_s , and r_t , respectively. For simplicity, we consider the car a cuboid with length, width, and height dimensions named l_{car} , w_{car} , h_{car} in the following calculation; the influence of the specific car shape on the drag force is included in the drag coefficient C_d .

105 The reactive force of the drag force, according to Newton's third law, applies to the air mass in the volume of the car in the opposite direction. The contribution of the car to the wind speed tendency χ_{car} [m s^{-2}] can be calculated from the reactive drag force by:

$$\chi_{\text{car}} = \frac{F_d}{m_{\text{air}}} = \frac{F_d}{\rho_{\text{air}} V_{\text{car}}} = \frac{C_d S_{\text{car}} r^2}{2 V_{\text{car}}} \quad (2)$$

where V_{car} [m^3] is the car volume and m_{air} [kg] stands for the mass of the air contained in the volume of the car. The car
110 volume can be calculated as

$$V_{\text{car}} = l_{\text{car}} w_{\text{car}} h_{\text{car}}, \quad (3)$$

and the projected frontal area of the rotated cuboid is:

$$S_{\text{car}} = w_{\text{car}} h_{\text{car}} |u_f| + l_{\text{car}} h_{\text{car}} |u_s| + w_{\text{car}} l_{\text{car}} |u_t| \quad (4)$$

where $u_f = r_f/r$ denotes the frontal component of the unit vector of relative car speed, $u_s = r_s/r$ its side component, and
115 $u_t = r_t/r$ the vertical top component.

Substituting equations 3 and 4 to 2 leads to



$$\chi_{car} = \frac{1}{2} C_d r^2 \frac{w_{car} h_{car} |u_f| + l_{car} h_{car} |u_s| + w_{car} l_{car} |u_t|}{l_{car} w_{car} h_{car}} = \frac{1}{2} C_d r^2 \left(\frac{|u_f|}{l_{car}} + \frac{|u_s|}{w_{car}} + \frac{|u_t|}{h_{car}} \right) \quad (5)$$

The tendency can then be decomposed into individual coordinate components by multiplying χ_{car} by unit vector components u_f , u_s , and u_t .

120 2.2 Calculation of the potential temperature tendency produced by car

The development of the module follows the implementation in Supplement F in Resler et al. (2024) and continues with the improvements described below; some similar basic concepts can also be found in Sun et al. (2026). The change of the air temperature ΔT_{air} [K] caused by the heat H_{car} [J] produced by the car follows:

$$\Delta T_{air} = \frac{H_{car}}{m_{air} c_p}, \quad (6)$$

125 where c_p [J kg⁻¹ K⁻¹] denotes the air specific heat.

The tendency $\chi_{\theta_{car}}$ [K s⁻¹] of the air potential temperature θ [K] imposed by the car can be calculated from the power of the car P_{car} [W] (heat produced by car per second):

$$\chi_{\theta_{car}} = \frac{P_{car}}{\rho_{air} c_p \Pi}. \quad (7)$$

The Exner function is written as Π ; see Maronga et al. (2020). This tendency applies to the air occupied by car.

130 The heat produced by a car per second is included in the traffic driver for each transportation line, car category, and time. This allows applying values obtained by different ways (simulations by transportation model, observations, etc.). A simple way to estimate these values is to derive them from the fuel consumed by the car and from the combustion heat of the fuel:

$$P_{car} = \frac{\phi_{car} \rho_{fuel} \Phi_{heat fuel}}{100 s_{car}}, \quad (8)$$

135 where ϕ_{car} is consumption in litres [l] of the car of given category per 100 km in given conditions, ρ_{fuel} [kg m⁻³] denotes the density of the fuel and $\Phi_{heat fuel}$ [J kg⁻³] is the combustion heat of the fuel.

2.3 Temporal application of the car-induced tendencies

This wind and temperature forcing is applied during the period when the car is running over a given location. Length of this time interval t_{tend} [s] is calculated from the car length and car speed as

$$t_{tend} = \frac{L_{car}}{s_{car}}. \quad (9)$$

140 The intervals t_{car} [s] between simulated car presence are derived from the transportation intensity as

$$t_{car} = \frac{U_{car}}{I_{cars}}. \quad (10)$$



where I_{cars} is the intensity of the stream in cars per U_{car} seconds.

An alternative implemented approach is to apply the appropriately normalised tendency over the entire simulation time. The normalization coefficient c_t [1] of the tendency is calculated as

$$c_t = \frac{t_{\text{tend}}}{t_{\text{car}}}. \quad (11)$$

This approach is less realistic but produces lower advection and potential temperature tendencies, thereby improving simulation stability. Performed tests suggest relatively small differences between these two approaches in the resulting averaged velocity, TKE, and potential temperature output fields (see Sect. 5.1).

3 Model implementation

- The Traffic model was integrated into the PALM model system as a standard module. It is enabled and configured through the configuration section `traffic_parameters`, which allows to switch on and off the application of wind and theta tendencies, set unit interval in which traffic intensities are provided, enable or disable calculation of the traffic stream slope from PALM terrain, set default values of traffic stream speed and speed instability which are used in case they are not provided in the traffic driver, and finally switch on and off application of speed disturbances and continuous application of tendencies.
- All parameters have reasonable defaults, and in most practical cases, no particular user settings are required.

3.1 Calculation of affected area and time

- The streams are provided in the driver as lines representing the centres of the streams. The affected grid cells are then identified for each car type separately based on car width and height during model initialisation. For the cells only partly contained in the traffic stream area, a fractional approach is applied. For computational efficiency, the fraction coefficients are not calculated as a full 3D intersection between the traffic lane and the grid cell, but are split into the 2D horizontal and 1D vertical intersections. Considering typical street slopes, inaccuracies caused by this simplification are negligible.

- In the temporal dimension, the model parameterises the alternating presence and absence of a car in any particular grid cell for each traffic stream and car type based on the traffic intensity and car speed as described in Sect. 2.3. In particular, it checks and, if needed, recalculates the current start and end times of the car presence, and the next start time of the car presence in every model time step. If the simulation time step overlaps with the car presence only partially, the fractional approach is applied, and only the corresponding fraction of the tendency is applied.

3.2 Input quantities

- The Traffic model needs two types of inputs: static and dynamic. The static data describe car types and characteristics (car dimensions and aerodynamic drag coefficient) and traffic lane characteristics (start, end, slope). The time-dependent data consist of transportation intensity, transportation flow speed, standard deviation of transportation flow speed, and heat produced by a running car. These values are provided separately for each stream, car category, and time.



The input data are provided to the model in a special NetCDF file `PIDS_TRAFFIC`, called the traffic driver, and its structure is described in detail in the PALM Input Data Standard (PIDS). Note that slope, speed, and speed standard deviation are optional items in the file.

175 4 Experiment setup

To evaluate the performance of the Traffic model implementation, an experiment was designed that analyses model simulations in three stages. First, a sensitivity study was conducted by running simulations with multiple configurations of the Traffic model and in different resolutions. The second stage evaluated the impact of the Traffic model against measurements taken in a dedicated field observation campaign. Finally, the influence of the model on air quality was tested in a stable winter situation.

180 4.1 Study area

The case study area for model evaluation is located in the centre of Prague, the capital of the Czech Republic (see Fig. 1); the modelled area is similar to the area used in the study Resler et al. (2024) with some modifications (see Sect. 4.2). The simulation covers the so-called “Legerova hot spot”, an area that specifically faces very heavy traffic. The hot spot is formed by the surroundings of Legerova and Sokolská streets, which are parts of the Prague Magistrála, the north-south-oriented arterial road through the Prague centre. The traffic in these streets is organised as a dual one-way system: Legerova in the south-north direction and Sokolská in the north-south direction. Traffic loads are around 35000 cars per day in each direction across three or four lanes, afflicted by frequent traffic congestion and poor air quality. The width of the street canyon is approximately 22 m for Sokolská and 24 m for Legerova Street, respectively. The properties of the street canyon strongly impact the local air quality. Both streets form a canyon with an aspect ratio of approximately 1.0 with predominantly right-angled blocks without any trees. The only plant canopy is a 50.0 m long, 80 cm high, and 70 cm wide linear shrub in Legerova Street, located on the right side of the road in the traffic direction.

The experiments analysed in the present study required certain adjustments to the original configuration of Resler et al. (2024). These changes reflect the situation during the observation campaign (see section 4.5), when part of Sokolská Street and the surrounding area were under reconstruction. Compared to the standard situation, four traffic lanes were reduced to two and rearranged. The transect between both streets, Rumunská Street, was closed. Three shipping containers, approximately 3.0 m high, were placed in the closed lanes. Changes in traffic organisation also influenced traffic on Legerova Street, where most of the traffic was concentrated into two central lanes. All these changes have been incorporated into the static driver of the PALM model, a file that describes the urban area in detail, following the PALM input data standard. The geodatabase used was the same as in Resler et al. (2024) (see Section 2.4.1). Preparation of the traffic data is described in Sect. 4.4.

200 4.2 Model configuration

In this study, we used the development version of the PALM model system release 26.10. The code was derived from the PALM GitLab master development branch on 10 September 2026 and includes small additional fixes. The exact code used

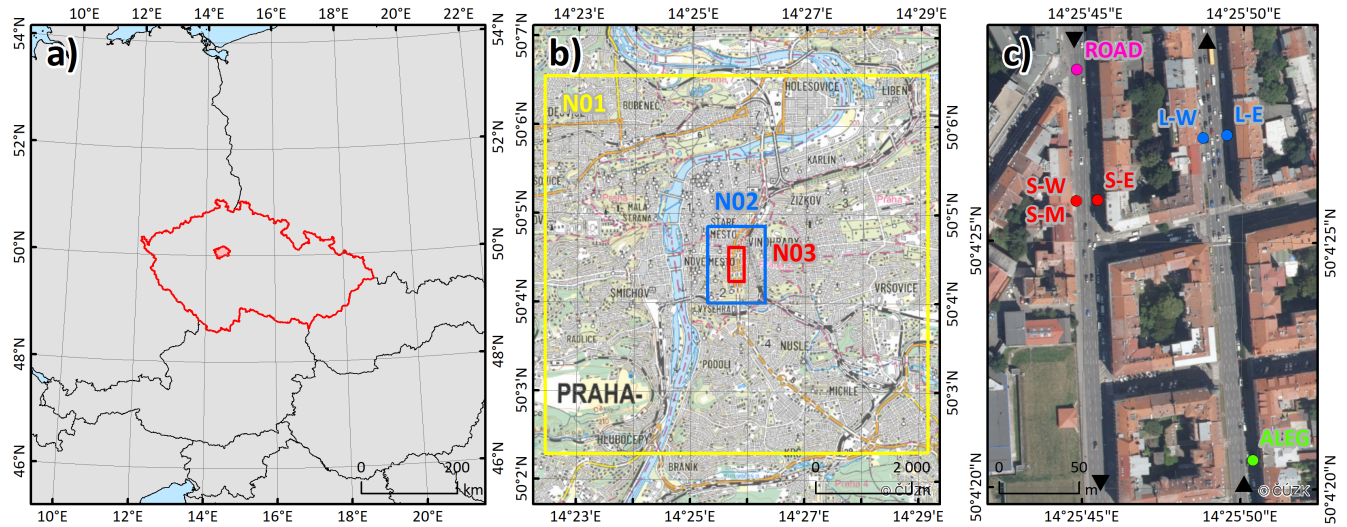


Figure 1. Location of the Czech Republic and the city of Prague in Europe (a), with three nested domains (N01 yellow, N02 blue and N03 red) over the Legerova hot spot (b), and individual measurement locations (c). S-W and S-E denote observation locations on the west and east sides of Sokolská Street, respectively; similarly, L-W and L-E denote observation locations on the west and east sides of Legerova Street. S-M is practically identical to S-W; exact position is visible on Fig. 2c. Black triangles indicate traffic direction: north-to-south in Sokolská and south-to-north in Legerova. The vector geodata for the maps on the left were provided by ESRI (Environmental Systems Research Institute, Europe NUTS 0 and NUTS 2 Boundaries); the topographical and orthophoto maps are provided through the web map service of the Czech Office for Surveying, Mapping and Cadastre – ČÚZK.

can be downloaded from the repository Resler et al. (2026). The model was configured with the LES core, solving the non-hydrostatic, filtered, Boussinesq-approximated Navier-Stokes equations. The subgrid stress tensor is modelled by the Deardorff (1980) 1.5-order closure involving Moeng and Wyngaard (1988) and Saiki et al. (2000) modifications. For spatial and temporal discretisation, the upwind-biased 5th-order differencing scheme Wicker and Skamarock (2002) and the 3rd-order Runge-Kutta time-stepping scheme (Williamson, 1980) were used, respectively. The solution of the pressure-Poisson equation in the projection step was configured to utilise the multi-grid scheme solver (e.g., Maronga et al., 2020) with the recently added Neumann boundary conditions on terrain and building surfaces. The PALM core utilises several modules necessary for an urban boundary layer simulations: mesoscale nesting Kadasch et al. (2021), online nesting Hellsten et al. (2021), land surface model (LSM; Gehrke et al., 2021), the radiative transfer model and the plant canopy model (RTM and PCM; Krč et al., 2021), the building surface model (BSM; Resler et al., 2017; Maronga et al., 2020), single-layer urban canopy model (SLUrb; Karttunen et al., 2025), and the chemical transport model (Khan et al., 2021). The chemistry was enabled only in the simulations described in Sect. 5.3.

The domain configuration has changed from the configuration used in Resler et al. (2024). PALM model was configured in three nested domains (see Fig. 1) to properly simulate all mixing layer scales and save computational resources. The parent domain N01 has an extent of 8000 m × 8000 m with a horizontal and vertical resolution of 20 m and a domain height of



2000 m. The middle domain N02 has an extent of $1200 \text{ m} \times 1600 \text{ m}$, a horizontal and vertical resolution of 4 m, and a height of 320 m. The fine-resolution domain N03 has an extent of $320 \text{ m} \times 704 \text{ m}$, a horizontal and vertical resolution of 1 m, and a height of 100 m (more than $3\times$ higher than buildings in the Legerova hot spot). No domains used vertical stretching. The parent domain utilises fractional surfaces within the SLUrb model (Karttunen et al., 2025); the remaining domains run in the building-resolving mode like in Resler et al. (2024). All the static drivers were prepared using the PALM-GeM tool (Bureš et al., 2026).

4.3 Initial and boundary meteorological conditions

225 The episodes selected for model evaluation were defined by the dates of the observation campaign (see Sect. 4.5). The first observation day was 28 May 2026 and the second was 18 June 2026.

The initial and boundary meteorological conditions were obtained from the assimilation cycle of the numerical weather prediction model ALADIN/CE operated by CHMI. The cycle consists of an analysis and a subsequent 6-hour forecast, carried out regularly at 0, 6, 12, and 18 h UTC. For upper-layer parameters, the analysis consists of two steps (referred to as the BlendVar method; Gustafsson et al., 2018). The first one is a sophisticated combination of the fields of the ARPEGE global model at larger scales with the mesoscale structures of the ALADIN model using the DFI blending method. The second one is the 3D-Var analysis applied on the result of the DFI blending step. Initial values of surface scheme prognostic parameters are updated from increments of temperature and relative humidity analysis performed at the measurement height of 2 m (Giard and Bazile, 2000).

235 The model uses a non-hydrostatic, fully elastic dynamical core and runs at a horizontal resolution of 2.3 km with 87 vertical levels. The physics package is based on the Canonical Model Configuration of the ALADIN System (Termonia et al., 2018) with further enhancements following Brožková et al. (2019). To process ALADIN outputs to the PALM dynamic driver, the PALM-meteo tool was used (Krč et al., 2026).

4.4 Traffic data

240 4.4.1 Prague traffic data

The average daily traffic intensities were based on the 2021 traffic census for the main roads, while the minor roads were assigned representative constant values. The temporal traffic profiles (except for Legerova and Sokolská streets) were derived from historical traffic count data provided by Technická správa komunikací hl. m. Prahy, a.s. (TSK), covering the periods from July 2020 to March 2021 and from June 2021 to February 2022. This dataset contained 5-minute traffic counts for passenger cars and heavy-duty vehicles ($> 3.5 \text{ t}$) for individual traffic lanes.

The intensity data were processed separately for each vehicle category. After quality control, including the removal of incomplete records, outliers, and locations with insufficient or unreliable observations, the data were aggregated to hourly directional traffic intensities. The average normalised weekly traffic profiles (168 hourly values) were then calculated for each counting location.



250 The normalised weekly profiles were classified using agglomerative hierarchical clustering with Euclidean distance and Ward's linkage, resulting in four representative clusters for each vehicle category. The mean temporal profiles were calculated for each cluster and subsequently assigned to the Prague road network based on the cluster membership of nearby counting stations and expert judgement. Since traffic direction is not distinguished in the PALM emission model, directional profiles were merged into non-directional profile combinations.

255 Finally, hourly temporal scaling factors were derived to disaggregate average daily traffic volumes into hourly emissions. In addition to the weekly profiles, monthly traffic variation factors from the TSK annual report were applied. National holidays were represented by modified weekly traffic patterns reflecting their typical impact on traffic intensity.

4.4.2 Legerova hot spot traffic data

To obtain actual car counts and speeds in Legerova and Sokolská, two cameras recorded traffic on the streets during the observation periods. The videos were then processed by the Ultralytics object detection package using the YOLO model (260 <https://www.ultralytics.com/>). The cars were tracked between two detection lines at known distances to estimate their speed (see Fig. A1). The distribution of cars in individual lanes was also estimated when possible. Missing values (mainly during periods when a camera battery was being replaced) were filled by linear interpolation between neighbouring periods.

In most cases, the cameras were mounted on a tripod standing on the ground at the observation site, recording traffic from a side view, meaning that cars in the lanes farther from the camera could be hidden behind cars in the closer lanes which resulted in some traffic data uncertainty. The exception was the placement of the camera on top of the container in Sokolská location during the second observation day, which provided more reliable results. The camera view angles were not standardised across sites and dates, introducing additional uncertainty for the lane detection algorithm and speed estimation due to perspective distortion. Even with these limitations, the data obtained in this way represent the traffic situation during the observational campaign more closely than the traffic census data described in the previous section, due to the traffic restrictions in effect at (270 the time of the campaign (see Sect. 4.1).

4.5 Observation campaign

To obtain measurements against which the modelled data could be validated, a dedicated observation campaign was conducted. Traffic in Sokolská flows southbound, whereas traffic in Legerova flows northbound. Both streets are oriented approximately north-south, with their longitudinal axes between 355° and 357°. A location where the two street canyons are most similar (275 was selected (Fig. 1). The locations were named Sokolská west/east pavement (S-W/S-E) and Legerova west/east pavement (L-W/L-E), respectively. To obtain additional information about the spatial gradient of the quantities across the street canyon, one of the observation stations was moved from position S-E to an additional location S-M next to the building wall on 18 June at 11:56 UTC (13:56 CEST). Photos of the locations are in Fig. 2.

280 The selection of the observation days was constrained by many limitations, e.g., the need for permissions from the city authority and the availability of observation tools and staff. Both dates 28 May 2026 and 18 June 2026 were selected for the most suitable meteorological conditions among the days for which a measurement permit had been granted: low wind speed



and no precipitation. The measurement campaign was held approximately between 04:00 and 17:00 UTC (06:00 and 19:00 local time/CEST). The first measurement day was primarily used to evaluate the method, mast configuration, and camera
285 placement. Moreover, on 28 May, only three measurement sets were available; therefore, measurements were not performed on the east side of Sokolská Street (S-E). From that reasons, we evaluate only the latter day. The observation data are shared in the repository Resler et al. (2026).

Meteorological masts were installed at the curbside, as close to the adjacent traffic lanes as possible (Fig. 2). Each mast was equipped with a WindSonic 60 two-dimensional ultrasonic anemometer (Gill Instruments, United Kingdom) for measuring
290 wind speed and direction, mounted at a height of 2.0 m above the ground. Its north was oriented along the street's longitudinal axis (i.e., between 355° and 357°). In addition, each mast was equipped with a MetConnect THP34 weather station (Gill Instruments, United Kingdom) measuring air temperature (TMP), relative humidity (RH), and atmospheric pressure (p), installed at a height of 1 m above the ground. All variables were recorded at a sampling frequency of 1 Hz. According to the manufacturer's specifications, the WindSonic 60 measures the wind speed over a range of 0–60 m s⁻¹, with an accuracy of
295 2 % root mean square error (RMSE) at the wind speed of 12 m s⁻¹, a resolution of 0.01 m s⁻¹, a response time of 0.25 s, and a starting threshold of 0.01 m s⁻¹. The wind direction is measured over a range of 0–360°, with an accuracy of 2° RMSE at the wind speed of 12 m s⁻¹, a resolution of 1°, and a response time of 0.25 s. For further technical details, see Gill Instruments Limited (2022, 2024).

In addition, two permanent professional monitoring stations are located in the vicinity: the air quality monitoring station
300 Prague 2-Legerova (ALEG; Fig. 1), (CHMI-Legerova, 2026), where measurements of nitrogen oxides, particulate matter, and carbon monoxide together with 10-minute traffic counts are available, and the meteorological station Prague 2-Karlov (PIPKAR01, WMO 11519), (CHMI-Karlov, 2026), located approximately 500 m from the measurement site on the roof top (between the south-west corners of the N02 and N03 domains in Fig. 1).

According to the measurements from the Prague 2-Karlov meteorological station (Fig. A3), the meteorological conditions
305 on 18 June were as follows: a southerly wind prevailed until approximately 06:30 UTC, after which it shifted to the north-west. From about 09:30 UTC onwards, the wind direction varied predominantly between 200 and 320°. Wind conditions were generally calm, with wind speed ranging between 1 and 3 m s⁻¹. The air temperature increased from 18 °C at 04:00 UTC to 30 °C in the afternoon.

5 Results

310 5.1 Impact of the Traffic model

To account for the influence of the Traffic model and its configurations on the results, four PALM simulations with the same PALM setup and input data but different configurations of the Traffic model were run. The tested configurations were:

- *eval2-n*: Traffic model disabled
- *eval2-t*: Traffic model enabled with default configuration

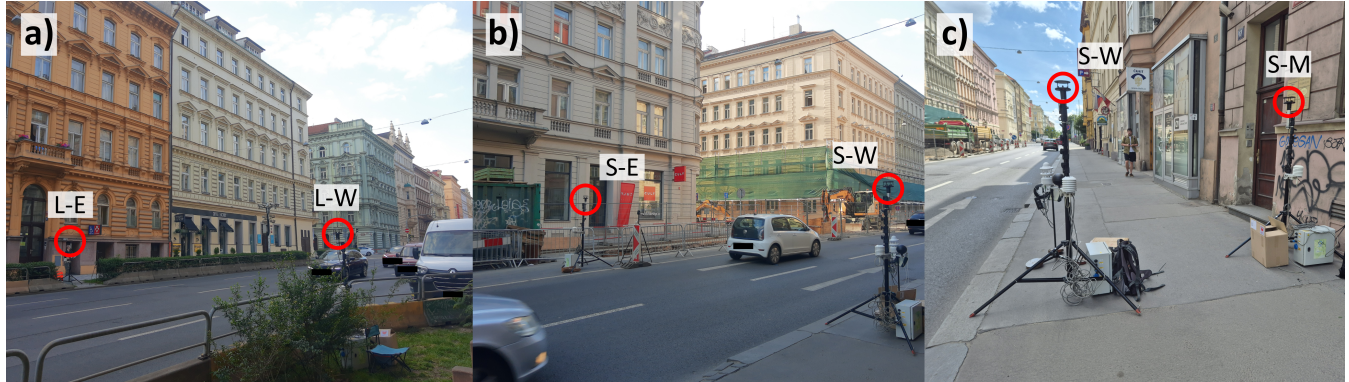


Figure 2. Overall view of the observation locations on 18 June 2026 in Legerova (a) and Sokolská (b) streets. Photo c) shows the situation at the Sokolská west (S-W) location after mast movement from Sokolská east (S-E), next to the wall (S-M; from 12:00 UTC until the end of measurement). Red circles mark the anemometer heads. Photos were made by Ondřej Vlček (a, b) and Jaroslav Resler (c).

315 – *eval2-s*: Traffic model enabled with simulation of stream speed instability disabled

– *eval2-c*: Traffic model enabled with simulation of stream speed instability disabled and continuous tendency enabled.

The comparison is performed in the street canyon coordinate system with the $u_{\perp}$ axis perpendicular to and $v_{\parallel}$ aligned with the street canyon axis.

A comparison of time-averaged wind components and turbulent kinetic energy in the centre of the left lane in Sokolská Street in domains N02 and N03 shows various impacts; see Fig. 3. The results for the 1 m resolution domain N03 show that the wind component aligned with the street canyon is modified by approximately $2.0\text{--}2.5\text{ m s}^{-1}$, and TKE is increased in the range $0.6\text{--}1.1\text{ m}^2\text{ s}^{-2}$. The perpendicular component has a lower magnitude, and it is modified by added traffic in the range $0.1\text{--}0.3\text{ m s}^{-1}$. Modifications in 4 m resolution domain are lower in ranges $0.7\text{--}1.7\text{ m s}^{-1}$, $0.1\text{--}0.5\text{ m}^2\text{ s}^{-2}$, and $0.1\text{--}0.3\text{ m s}^{-1}$, respectively. The 4 m resolution is not sufficient to fully describe turbulent flow in the given street canyon (5–6 grid boxes across the canyon width), however, the differences between results for 1 m and 4 m resolutions can be mainly attributed to the fact that in 4 m resolution, typical car dimensions become smaller than the grid size. As a result, a significant part of the vehicle-induced effects becomes a subgrid effect.

Consider a simple case where the car and its movement are aligned with the grid cell. In the model, the forces on the grid cell from the car's frontal area are applied to the entire cell. For a typical passenger car with a frontal area of $2.5\text{--}3.0\text{ m}^2$ in a 4 m grid (area 16.0 m^2), this can be $5.0\text{--}6.5 \times$ larger than the area affected in reality. This is compensated for by decreasing the tendency by the fractional scaling factor as described in Sect. 3.1. However, this discretisation issue can influence the distribution of forcing inside the street canyon (see the example in Fig. A2), and it definitely affects the wind shear produced in the model. This issue is further discussed in Sect. 6.2.

The comparison of the different modelling approaches for the temporal application of the tendencies suggests minor differences in the aligned component $v_{\parallel}$ with maxima up to 0.4 m s^{-1} and in the perpendicular wind component $u_{\perp}$ with similar



maxima up to 0.2 m s^{-1} . The modification of the TKE is typically largest in the case of the default model configuration *eval2-t* (modelling of the car presence and variability of the speed) and smallest in the case of the configuration *eval2-c* (with continuous application of the tendencies) with differences up to $0.3 \text{ m}^2 \text{ s}^{-2}$. Note that this comparison is valid for time-averaged values; differences in instantaneous values are naturally large, as shown by 1 s outputs available in Resler et al. (2026).

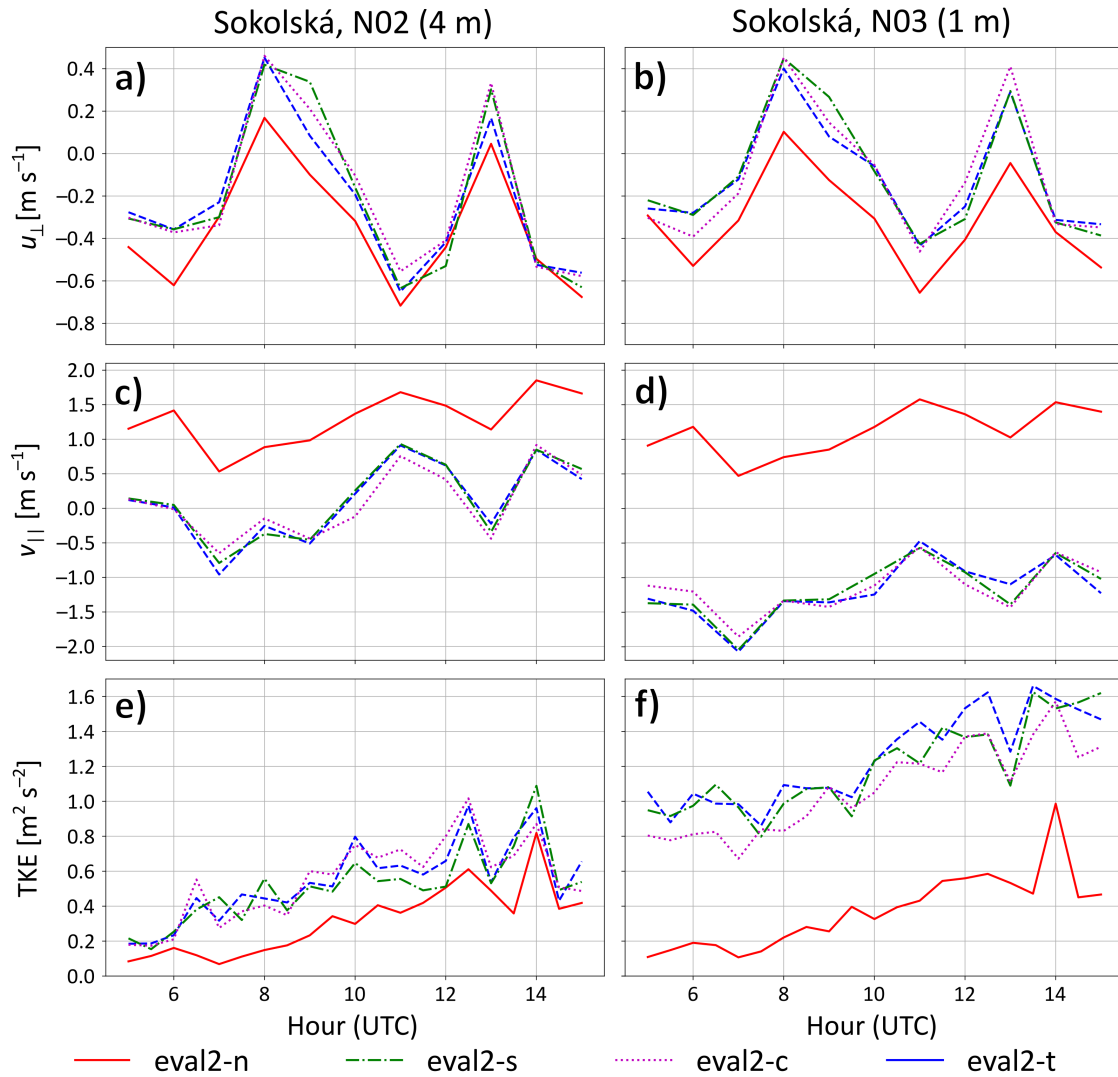


Figure 3. Comparison of hourly-averaged wind components $u_{\perp}$, the perpendicular wind component to the street canyon orientation (first row), $v_{\parallel}$, aligned with canyon orientation (middle row), and 30-minute averages of the turbulent kinetic energy (TKE; bottom row) in the centre of the left transportation line in Sokolská Street in the S-W location (see Fig. 1). Note that traffic direction is north-to-south. The left column (a, c, e) shows results for the middle-domain (N02), and the right column (b, d, f) shows the fine-scale domain (N03). Detailed configuration is at the beginning of Sect. 5.1.



340 Spatial distribution of the TKE and wind speed/direction in the street canyons for all configurations is shown in Fig. 4. It shows that the influence of the additional traffic-induced momentum is not limited to the traffic lanes but extends across the full width of the street canyons. Note that the visible artifacts of TKE in both streets are caused by artificial terrain steps created as a result of grid discretisation.

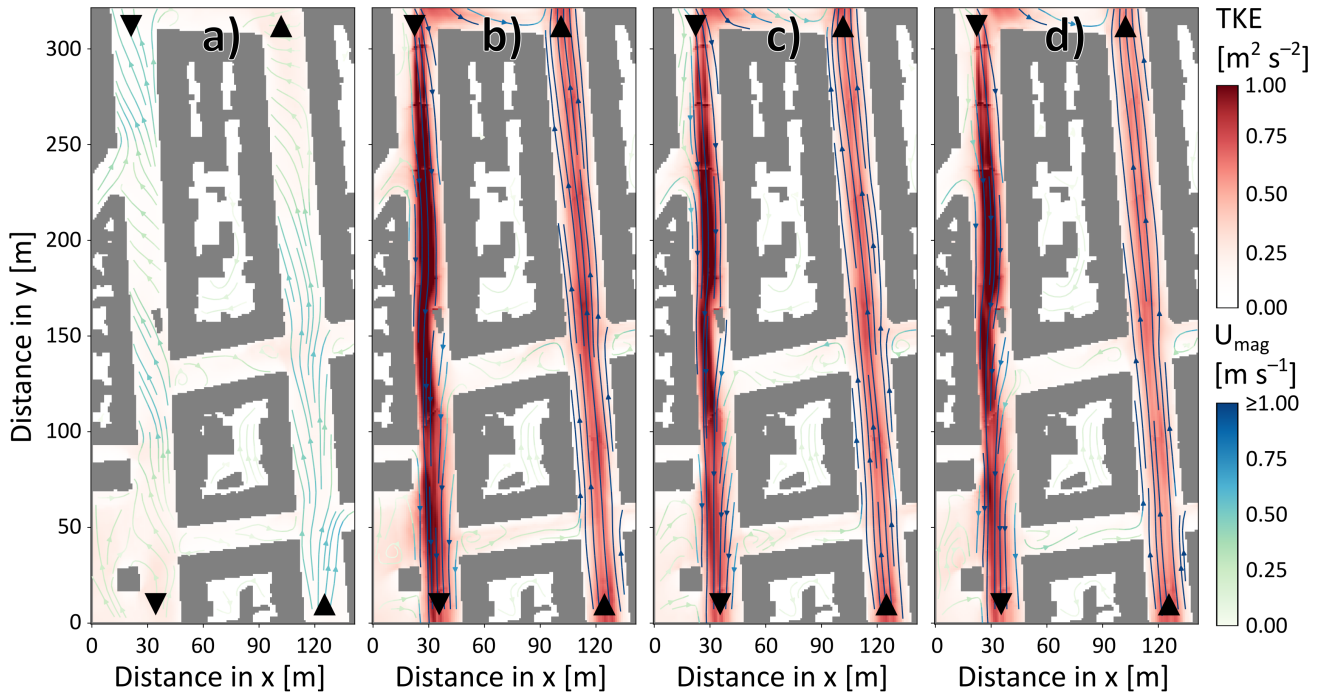


Figure 4. Influence of the Traffic model on the flow and TKE in the streets of interest for following configurations: (a) Configuration *eval2-n*, (b) configuration *eval2-t*, (c) configuration *eval2-s*, and (d) configuration *eval2-c*. Detailed description of the configurations is given at the beginning of Sect. 5.1. Maps show the one-hour average of the turbulent kinetic energy TKE during the morning rush hour from 07:00 to 08:00 UTC. Maps represent the average through the first 3 grid cells above ground. Black triangles indicate traffic direction: north-to-south in Sokolská and south-to-north in Legerova.

The influence of the traffic model on the potential temperature field is shown in Fig. 5. These graphs demonstrate that car-
345 induced heat significantly affects potential temperature after the start of the intensive morning traffic under stable conditions during the early morning hours from 03:00 to 05:30 UTC (corresponding to 05:00–07:30 of local time CEST) with increases exceeding 1.5 K. When the convection starts, the impact of the car-produced heat decreases to values between 0.5–1.0 K.

Spatial distribution of these differences at 05:00 UTC (07:00 local time CEST) are shown in Fig. A4. The maximum impact is in the main street canyon with heavy traffic, but it also propagates to surrounding auxiliary streets with low traffic and to
350 open courtyards. The closed courtyards are affected much less.

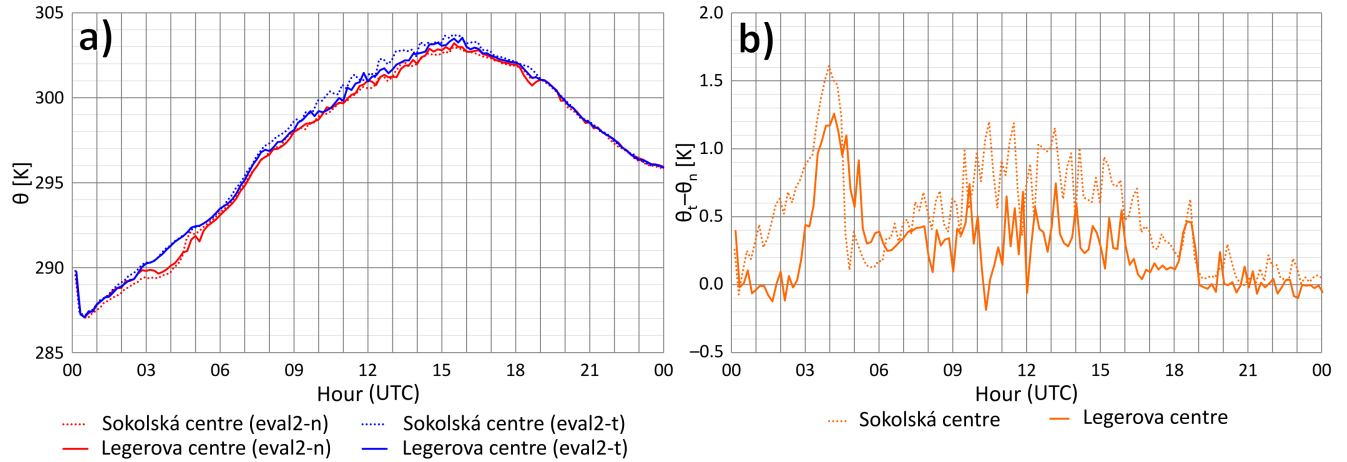


Figure 5. Simulated 10-minute-averaged diurnal profiles of the potential temperature (θ) in the centre of the transportation line in Sokolská and Legerova streets. Both locations are between the measurement spots S-W and S-E, or L-W and L-E, respectively (see Fig. 11). The left graph (a) shows absolute simulated values for configurations without (*eval2-n*) and with (*eval2-t*) the Traffic model; the right graph (b) shows the difference between both configurations (*eval2-t*–*eval2-n*). A detailed description of the configurations is at the beginning of Sect. 5.1.

5.2 Model comparison with field measurements

The observed and modelled values from configurations *eval2-t* (Traffic model default) and *eval2-n* (Traffic model disabled) for the 1 m resolution domain N03 in observation locations S-W, S-E, and L-W are shown in Fig. 6. Fig. 7 shows graphs of the TKE in locations S-W, S-E, S-M, and L-W. Note that S-E measurements were available only in the morning hours and S-M in the afternoon hours (see Section 4.5). As the two-dimensional ultrasonic anemometer provides only horizontal components of the wind speed, the horizontal part of the turbulent kinetic energy TKE_h is compared. This quantity is defined as $\text{TKE}_h = 0.5 (\langle u'u' \rangle + \langle v'v' \rangle)$, where u' and v' denote the perturbation of the u and v wind component, respectively, and $\langle \cdot \rangle$ denotes the 30 min time average.

The comparison for location S-W shows a correction of the aligned wind component $v_{||}$ by up to -3.0 m s^{-1} in the *eval2-t* configuration, bringing the modelled values very close to the observations. Note that this adjustment reverts the actual wind direction. The Traffic model decreases the perpendicular component by approximately $0.2\text{--}0.6 \text{ m s}^{-1}$ and the correction slightly overestimates the observed values by approximately $0.1\text{--}0.2 \text{ m s}^{-1}$. TKE_h increases in the range of $0.3\text{--}0.7 \text{ m}^2 \text{ s}^{-2}$ pushing the model to the observed values but systematically slightly overestimating the observed values. It shows that, although the Traffic model does not include an additional subgrid turbulence production term, the additional momentum from the vehicles creates wind shear in the model, which significantly increases TKE.

At the L-W location, the aligned wind component increases in the range of $0.5\text{--}1.5 \text{ m s}^{-1}$ in the *eval2-t* simulation, which overestimates the influence of traffic most of the time. The perpendicular component is adjusted by up to 0.3 m s^{-1} and these adjusted values agree well with the observed values. TKE_h is adjusted in the range of $0.0\text{--}0.2 \text{ m}^2 \text{ s}^{-2}$ and the adjusted values



slightly underestimate the observed counterparts during the morning hours and overestimate during the afternoon hours when
370 observed values significantly dropped.

At the S-E location, the aligned wind component $v_{||}$ decreases by about $0.3\text{--}0.5\text{ m s}^{-1}$ and fits the observations well while
the $u_{\perp}$ component increases by about $0.1\text{--}0.3\text{ m s}^{-1}$ with only a minor influence on the fit with observations. TKE_h increases
by about $0.2\text{--}0.6\text{ m}^2\text{ s}^{-2}$ and fits the observations almost perfectly. The observation instrument was moved from the S-E
location to the S-M location close to the building wall in the afternoon. Fig. 7b shows that even at this location located farther
375 from the traffic stream, the TKE_h increases by about $0.1\text{--}0.2\text{ m}^2\text{ s}^{-2}$ bringing the modelled values significantly closer to the
observations.

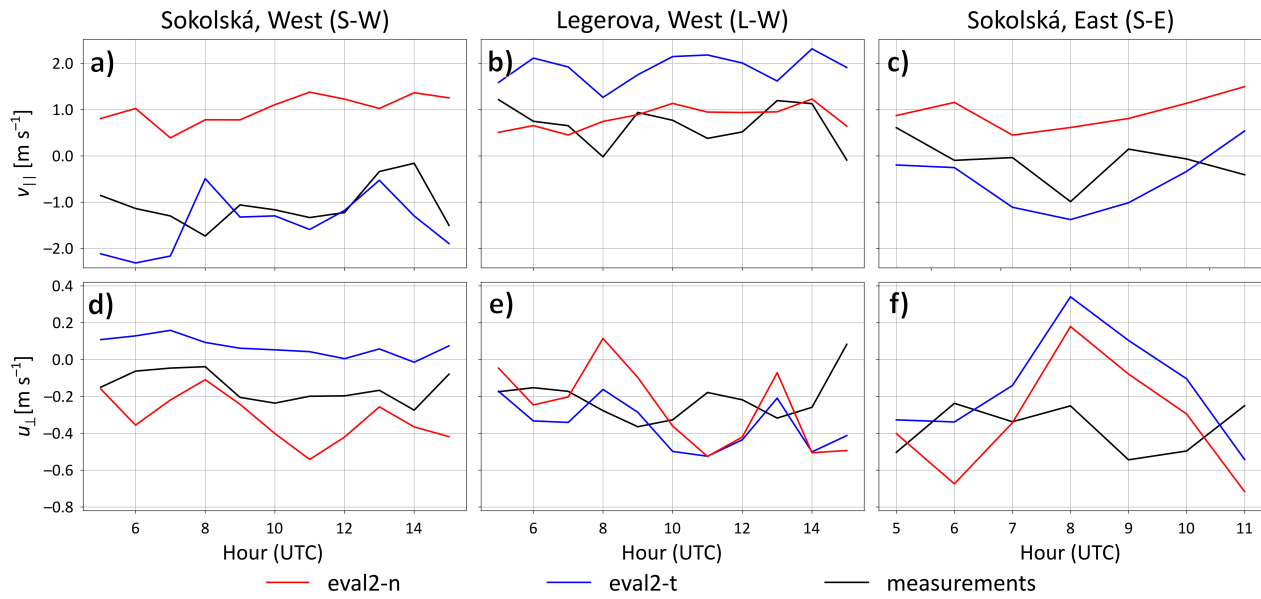


Figure 6. Comparison of the simulated wind components $v_{||}$ -along the street, $u_{\perp}$ -perpendicular to the street with measurements in locations S-W (a, d), L-W (b, e), and S-E (c, f). Compared simulations are with Traffic model (*eval2-t*) and without Traffic model (*eval2-n*). The values represent the one hour time average, the time symbolize the start of the averaging interval.

To obtain a detailed view of the composition of the turbulent spectra, the modelled and observed spectrum of TKE_h multiplied by frequency (f [Hz]) was calculated from the observed and modelled values of the velocity components with 1 s
sampling from the 1 hour time interval between 06:00 and 07:00 UTC (morning rush hours). The horizontal spectral density is
380 defined as $S_h = 0.5 (S_{uu} + S_{vv})$, where S_{uu}, S_{vv} [$\text{m}^2\text{ s}^{-1}$] denote the power spectral density for component u, v respectively
computed as a periodogram using the Fast Fourier transform (FFT) smoothed by a discrete Gaussian filter with 5 frequency
bands filter width. The results are shown in Fig. 8. The graphs show that the Traffic model increases S_h and brings them
very close to the observed counterparts in both S-W and L-W locations. The results show that incorporating the Traffic model
modifies the spectrum not only at low frequencies but also at high frequencies close to the time step of the observations and

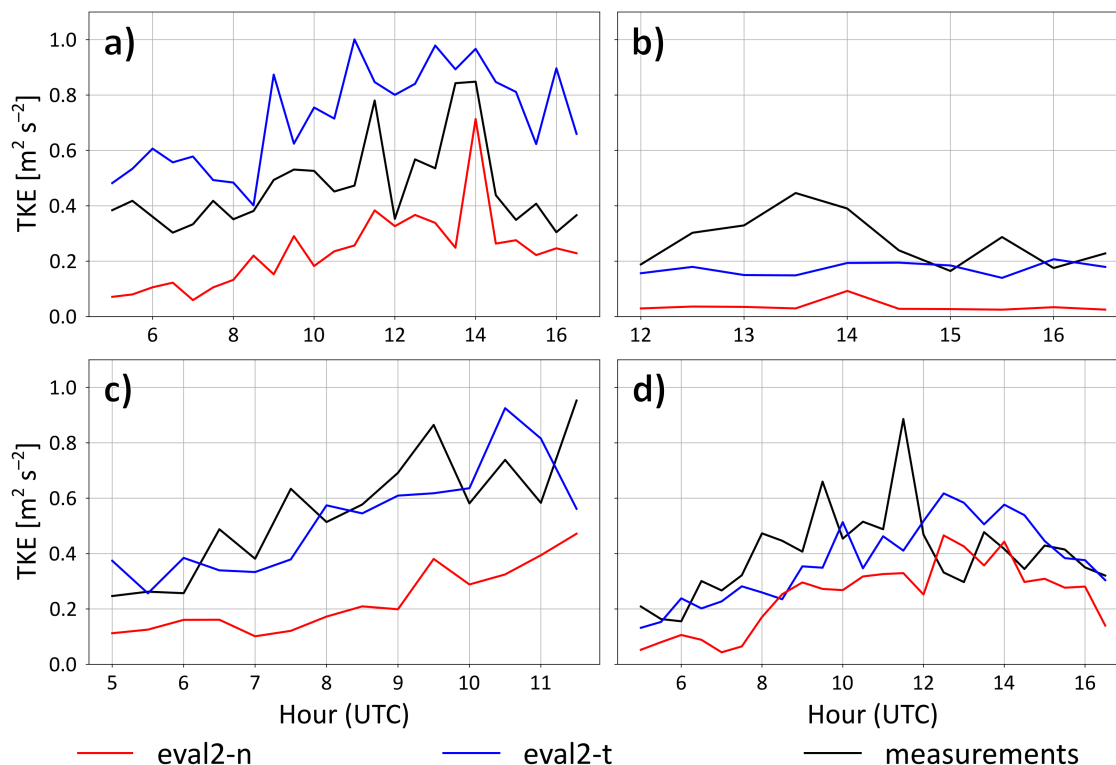


Figure 7. Comparison of the simulated horizontal turbulent kinetic energy TKE_h calculated from 1 s modelled with values calculated from measurements in locations S-W (a), S-M (b), S-E (c), L-W (d). Compared simulations are with Traffic model (*eval2-t*) and without Traffic model (*eval2-n*). The values represent the 30 minutes time average, the time symbolize the start of the averaging interval.

the model. In both locations, the simulated spectra are most improved at high frequencies with a period below 30 s while the smallest adjustment is achieved for frequencies with a period around 100–200 s in location L-W.

Tables 1 and 2 provide information on the spatial gradient of the quantities across the street canyon. They show the modelled and observed hourly-averaged values of the aligned wind speed component and TKE_h for all observation locations in Sokolská Street and for the centre of the left traffic lane. They show that the model captures the decrease in the influence of the traffic stream with increasing distance well. Compared to the model, the observations show greater variability over time (e.g., a noticeable decrease of wind velocity between 13–15 and an increase in preceding and following hours), which can be attributed to the variability of the meteorological conditions not fully captured in the model boundary conditions. The daytime averages of the wind component $v_{||}$ show a significant improvement in the modelling results with the Traffic model, with a slight overestimation of the influence of the traffic stream on airflow, mainly in location S-E. Possible reasons for this behaviour are discussed in Sect. 6. The Traffic model significantly increases the daily values of TKE_h , which agree well with the observed values, although it slightly overestimates them at the S-W and underestimates them at the S-E and S-M locations.

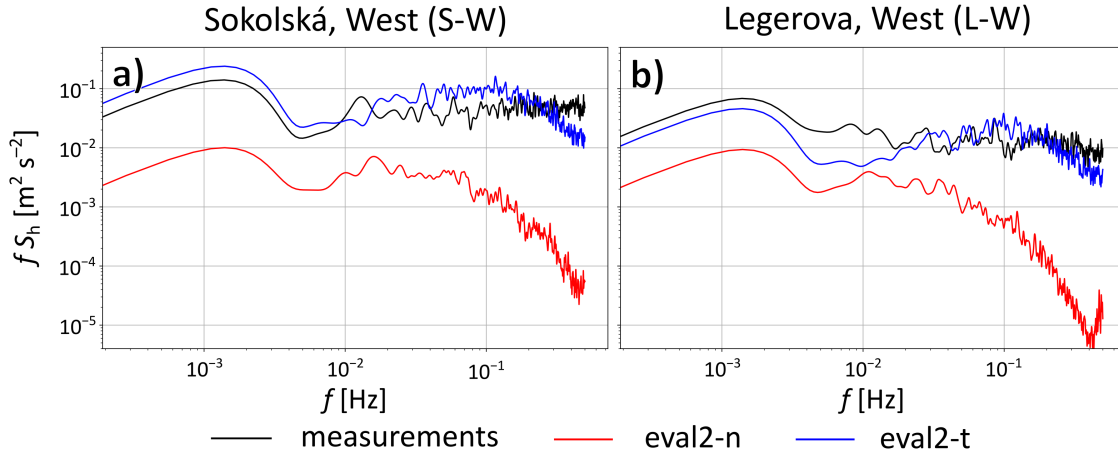


Figure 8. Comparison of the simulated and observed horizontal logarithmic power spectral densities ($f S_h$) in locations in S-W (a) and L-W (b). The graphs show a processed time series for the period of the morning traffic peak 06:00–07:00 UTC.

Table 1. Hourly-averaged values of the traffic-direction-oriented velocity component $v_{||}$ [m s^{-1}] across Sokolská Street on 18 June 2026. Locations S-E, S-W, and S-M are shown in Fig. 2, traffic lane position Sokolská centre is between S-E and S-W.

point: time (UTC)	S-E			Sokolská centre		S-W			S-M		
	mast	<i>eval2-t</i>	<i>eval2-n</i>	<i>eval2-t</i>	<i>eval2-n</i>	mast	<i>eval2-t</i>	<i>eval2-n</i>	mast	<i>eval2-t</i>	<i>eval2-n</i>
05–06	0.61	−0.20	0.87	−2.15	0.86	−0.86	−2.12	0.81	—	−0.54	0.06
06–07	−0.10	−0.25	1.16	−2.34	1.11	−1.14	−2.31	1.03	—	−0.60	0.08
07–08	−0.03	−1.11	0.45	−2.80	0.45	−1.30	−2.16	0.39	—	−0.59	−0.00
08–09	−0.99	−1.38	0.62	−2.30	0.7	−1.73	−0.49	0.78	—	−0.23	0.09
09–10	0.15	−1.01	0.81	−2.26	0.82	−1.06	−1.32	0.78	—	−0.43	0.09
10–11	−0.07	−0.33	1.14	−2.10	1.14	−1.17	−1.30	1.11	—	−0.41	0.14
11–12 ^{*1}	−0.41	0.54	1.50	−1.44	1.50	−1.33	−1.59	1.38	—	−0.57	0.12
Average	−0.12	−0.53	0.94	−2.20	0.94	−1.23	−1.61	0.90	—	−0.48	0.08
12–13	—	−0.03	1.34	−1.83	1.31	−1.22	−1.18	1.23	−0.88	−0.45	0.11
13–14	—	−0.96	0.94	−2.07	1.00	−0.34	−0.53	1.03	−0.17	−0.23	0.12
14–15	—	0.35	1.49	−1.67	1.46	−0.16	−1.30	1.37	−0.12	−0.50	0.08
15–16	—	−0.07	1.40	−2.13	1.33	−1.50	−1.89	1.26	−0.93	−0.55	0.12
Average	—	−0.18	1.29	−1.93	1.28	−0.81	−1.23	1.22	−0.53	−0.43	0.11

^{*1} Station was moved from S-E to S-M location at 11:56 UTC.



Table 2. Hourly-averaged values of TKE_h [$\text{m}^2 \text{s}^{-2}$] across Sokolská Street on 18 June 2026. Locations S-E, S-W, and S-M are shown in Fig. 2, , traffic lane position is between S-E and S-W.

point: time (UTC)	S-E			Sokolská centre		S-W			S-M		
	mast	<i>eval2-t</i>	<i>eval2-n</i>	<i>eval2-t</i>	<i>eval2-n</i>	mast	<i>eval2-t</i>	<i>eval2-n</i>	mast	<i>eval2-t</i>	<i>eval2-n</i>
05–06	0.26	0.18	0.13	0.86	0.10	0.40	0.69	0.09	—	0.10	0.01
06–07	0.55	0.22	0.17	0.89	0.16	0.40	0.75	0.13	—	0.10	0.01
07–08	0.54	0.28	0.16	0.84	0.15	0.38	0.77	0.14	—	0.07	0.02
08–09	0.55	0.34	0.19	0.93	0.20	0.37	0.66	0.19	—	0.08	0.03
09–10	0.79	0.41	0.29	0.95	0.27	0.51	1.00	0.24	—	0.12	0.03
10–11	0.81	0.52	0.29	1.09	0.28	0.53	0.96	0.23	—	0.16	0.03
11–12* ¹	0.77	0.55	0.47	1.23	0.42	0.63	1.13	0.35	—	0.21	0.04
Average	0.61	0.36	0.24	0.97	0.23	0.46	0.85	0.18	—	0.12	0.02
12–13	—	0.73	0.51	1.4	0.49	0.51	1.03	0.39	0.27	0.17	0.03
13–14	—	0.70	0.41	1.28	0.44	0.69	1.20	0.35	0.39	0.15	0.03
14–15	—	0.60	0.71	1.35	0.64	0.72	1.15	0.53	0.36	0.2	0.06
15–16	—	0.51	0.34	1.17	0.35	0.4	0.98	0.3	0.23	0.17	0.03
Average	—	0.64	0.49	1.30	0.48	0.58	1.09	0.39	0.31	0.17	0.04

*¹ Station was moved from S-E to S-M location at 11:56 UTC.

5.3 Impact on the air quality

As noted earlier, the Traffic model for the PALM model system has been developed to address issues identified during the air quality validation campaign (Bauerová et al., 2025) and the subsequent sensitivity study in the Legerova hot spot (Resler et al., 2024). The main issue identified was a strong, unrealistic overestimation of the modelled concentrations during certain stable, low-wind-speed situations with the most evident occurrence of this phenomenon observed in the afternoon of the first day of episode *s6* (13–15 February 2023). This section evaluates sensitivity of the modelled concentrations on the forcing induced by traffic on the first day of the simulation from Resler et al. (2024). This new simulation represents a rerun of the original experiment with the current model code including the newly added Traffic model.

The PALM model, its configuration, and input data have received important updates since the sensitivity study, which affect the simulated concentration. The model update most relevant for the sensitivity study was the inclusion of Neumann boundary conditions in the multigrid pressure solver, which significantly reduced the pressure field divergence residua near the surfaces (ground, walls, roofs). Configuration improvements include a new setup with three nested domains with the finest domain resolution of 1 m, utilisation of the recently developed single-layer urban canopy model (SLUrb; Karttunen et al., 2025) in the parent 20 m resolution domain, and different settings of the Synthetic Turbulence Generator in PALM. The emission input data were prepared from the same foundation data using the FUME emission processor (Belda et al., 2024). The new version 26.08 of this model got significant improvements with the addition of the meteorological plume rise for point sources and



emission dissolving for point and area sources. These new features were utilised in the preparation of the new emission inputs, which significantly reduced spatial gradients in the resulting emissions. The meteorological inputs, which were taken from the same ICON model predictions provided by the Deutscher Wetterdienst (Reinert et al., 2020), were processed into PALM inputs with the new version 2.8 of the PALM-meteo tool (Krč et al., 2026). This version includes many improvements, mainly in the processing of the vertical structure of the meteorological fields. For other details, see the original study Resler et al. (2024).

To account for the influence of the Traffic model and its processes, four PALM simulations with the same PALM setup and input data but different configurations of the Traffic model were run. The tested configurations were:

- *s6-n*: Traffic model disabled
- *s6-h*: Traffic model enabled with only theta tendency applied
- *s6-d*: Traffic model enabled with only air advection tendency applied
- *s6-t*: Traffic model enabled with default configuration (both tendencies applied).

The graph in Fig. 9 shows a comparison of the modelled PM₁₀ concentrations for selected points: monitoring station ALEG studied in (Resler et al., 2024), observation location S-W, observation location L-W, and a selected hot-spot point in the centre of the intersection of the streets Sokolská and Na Bojišti, approximately 80 m north from the S-W location, where the modelled concentrations reach maxima (ROAD). The comparison of the vertical profiles at 17:20 UTC (concentration peak) is given in Fig. A6. Note that the building height in both street canyons ranges from 20 to 28 m. The graphs indicate that, despite many important improvements in the new model version and its setup, a model instability and unrealistically high concentrations remain visible in configuration *s6-n* in some areas at the previously identified times (17:00–19:00 UTC), while in simulation *s6-t* with the Traffic model enabled, no such instabilities occur and the concentration peaks are significantly decreased. An exception is the situation in the area of the ALEG station (Fig. 9c) at hours 6:00–12:00 and 19:00–21:00 where the concentrations in setups *s6-t* and *s6-d* are higher than in setups *s6-n* and *s6-h*. The reasons for this behaviour are discussed in Section 6.3.

The spatial distribution of the one-hour averages of the PM₁₀ concentrations for various simulation setups for the period 17:00–19:00 UTC is shown in Fig. 10. Similar maps for the morning peak period 6:00–7:00 UTC are shown in Fig. A7. Unrealistically high concentrations occur in several locations of the street canyons in the simulation without the Traffic model at these particular times, mainly in the Sokolská street in the north direction from the observation locations. This effect is much reduced in *s6-h* and is not present in simulations *s6-d* and *s6-t*. The added heat in *s6-h* influences the stratification leading to a significant decrease of the concentrations to values typically in the range of 40% to 90% of the original values in peak hours. However, the horizontal pattern remains similar. The added advection forcing in *s6-d* and *s6-t* decreases the concentration peaks to typically 27%–55% of the original value, and also significantly influences the spatial pattern of the concentrations by transporting pollutants along the street canyon. The spatial distribution is much flatter and more closely matches that measured by the sensor network during the validation campaign Bauerová et al. (2025).



445 All these cases show that transportation-produced momentum and heat forcing significantly influence street canyon ventilation and, consequently, air quality, and their inclusion in the model is necessary for reliable realistic simulations of stable low wind meteorological conditions. A new validation of the improved PALM model system, including the new Traffic model against the observation dataset collected during the campaign Bauerová et al. (2025), is an ongoing task.

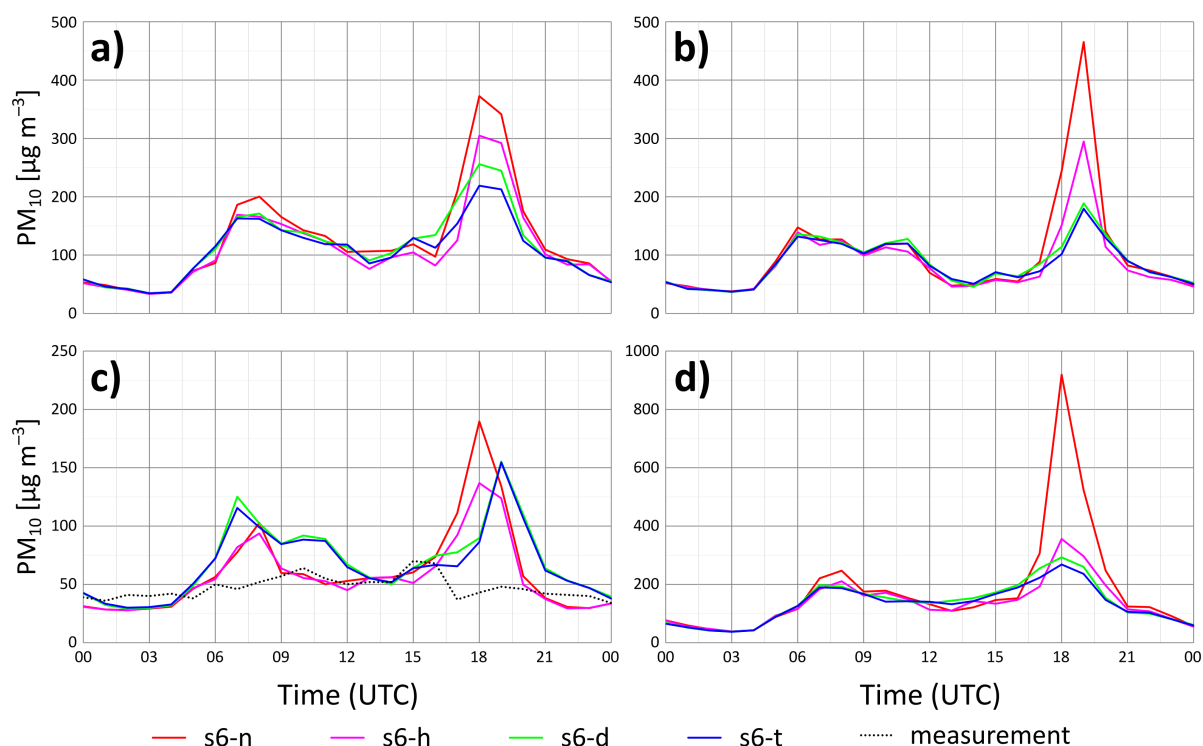


Figure 9. Hourly-averaged concentrations of PM_{10} on 13 February 2023 for observation locations S-W (a), L-W (b), the automatic emission measurement station ALEG (c), and the hot spot point ROAD (d). Note that all points are averages for layers 2 and 3; ALEG is the average for layers 4 and 5 to reflect sensor height. Detailed description of the setups *s6-n*, *s6-h*, *s6-d*, and *s6-t* is in Sect. 5.3.

6 Discussion

450 6.1 Uncertainties in the model and data

High-fidelity simulations of realistic urban environments are typically influenced by specific factors that are not fully reflected in the model. Although this study uses a spatial resolution of 1 m and unique, precise input data, significant uncertainties still influence the results. These uncertainties can be divided into several categories.

455 Firstly, some relevant factors are subgrid-scale or have subgrid-scale effects. In particular, the observation spot S-E could be influenced by temporary traffic cones placed before and after the location (see Fig. 11a,b). They can cause micro-scale eddies,

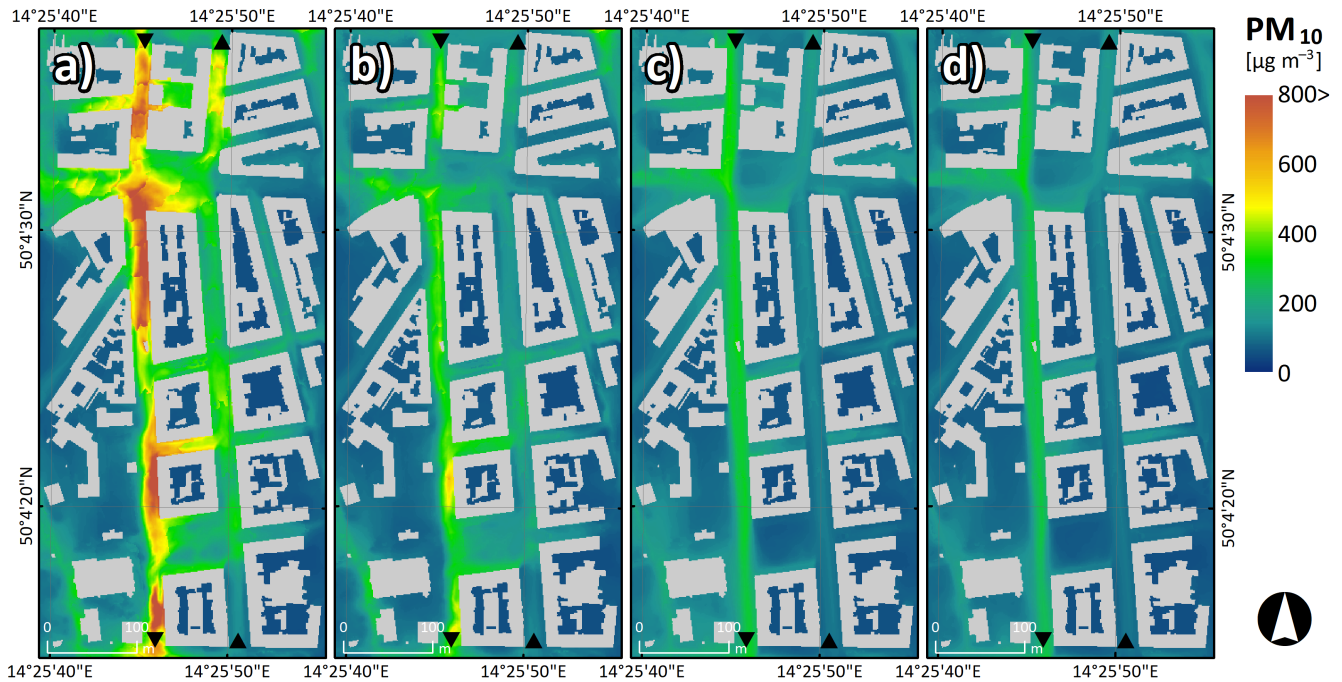


Figure 10. Simulated hourly-averaged concentrations of PM_{10} in the domain N03 at level 2.0 m (averaged layers 2 and 3) on 13 February 2023 for the period 17–18 UTC. Results corresponds to the *s6-n* (a), *s6-h* (b), *s6-d* (c), and *s6-t* (d) setups. Black triangles indicate traffic direction: north-to-south in Sokolská and south-to-north in Legerova.

reduce wind flow, and increase TKE in reality. Due to their small dimensions, their inclusion in the model is complicated. They may contribute to the overestimation of the impact of the Traffic model on the modelled wind speed and the underestimation of the impact on TKE in this location. Similarly, a smaller effect can be expected from the building machinery, tools, and railing present in the vicinity of this location, which were not included in the model. Additional tests would be needed to confirm this hypothesis.

Another significant effect of subgrid features is caused by the concrete barriers in Legerova Street (see Fig. 2a); they are ≈ 10 cm wide and ≈ 60 cm high, and they extend along the entire street (see Fig. 11d). In the L-E location (see Fig. 2a), there is also a hedge line after the concrete barrier stretching along the entire line (see Fig. 11c), which was modelled as a resolved plant canopy. However, due to its dimensions (width ≈ 70 cm and height ≈ 80 cm) and the grid size, the modelled dimensions differ from reality. Moreover, the leaf area density $LAD = 3.0 \text{ m}^3 \text{ m}^{-2}$, was specified only by an expert estimate. These barriers and hedges likely significantly modified the lower part of the primary vortex in the street canyon and influenced airflow between the street and the pavement where the observation spot was located.

Another type of model uncertainty is connected to the model gridding structure. This simulation uses a standard PALM Cartesian grid in which each cell is either 100 % fluid or 100 % obstacle. This creates artificial steps in the representation of non-flat terrain and all buildings not aligned with the grid. These steps strongly affect the flow and surface energy balance in

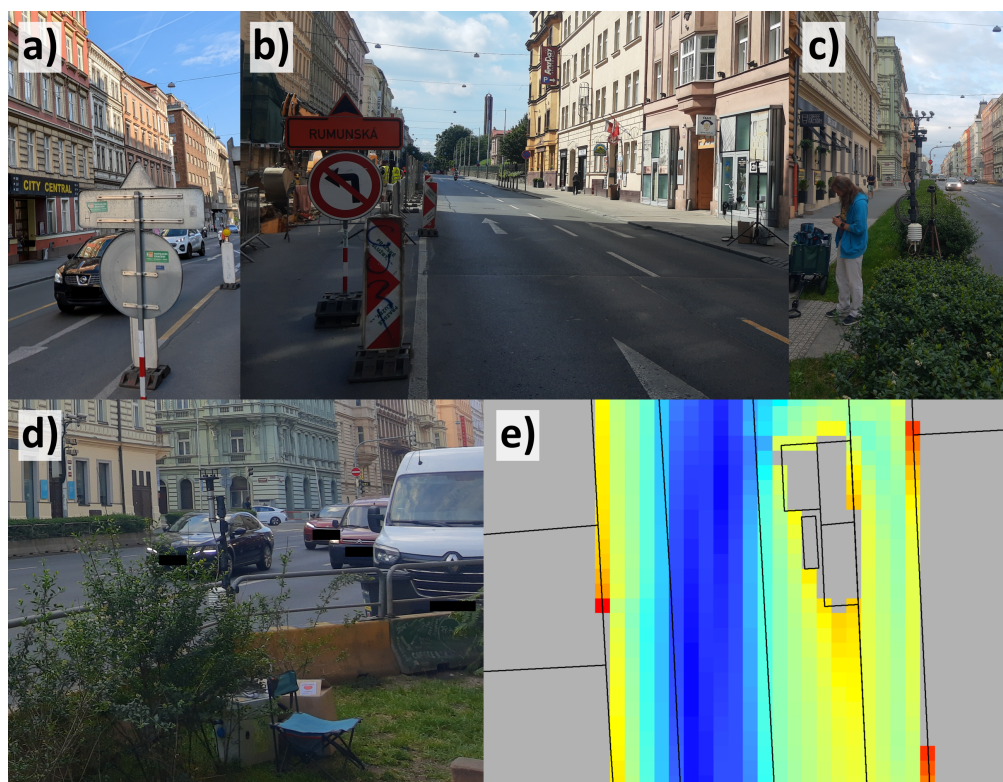


Figure 11. Subgrid features around observation locations: Placement of the cones before the observation location S-E - north-facing view (a) and south-facing view (b), hedges around locations L-E (c), and the end of the parking line close to L-W in Legerova street (d). Discretisation of the street canyon and the building containers in Sokolská street around the location S-E. It also indicates by colours the influence of the discretization on the modelled $v_{||}$ in $s6-t$ on 13 February 2023 at 14:00 UTC (e). Photos were made by Jaroslav Resler (a, b) and Ondřej Vlček (c, d).

their vicinity, study Resler et al. (2021) discussed their practical effects. Fig. 4 shows the influence of artificial steps in terrain on the modelled TKE_h . The effect for walls is similar. In simulations utilising the chemical module, steps also influence the spatial distribution of pollutant concentrations. The effect is strongest when the emission sources are close to the surface (see Fig. 10). The situation is even worse near the observation location S-E. Due to a slight deviation of the street canyon orientation from the model coordinate system, a “building” grid was added on the north side of the container as the effect of discretisation (see Fig. 11e). This creates an artificial south-facing wall, causing flow wakes that have no counterpart in reality and probably influence the evaluation at the observation location S-E.

These gridding effects can be mitigated in two ways. In this particular simulation, properly rotating the model domain could align buildings on both streets with the model coordinate system, avoiding most artificial steps. However, rotation will not work for the other streets in the domain; it also cannot fix the terrain steps. A more general approach is the cut-cell method, which avoids these effects by simulating arbitrarily oriented and positioned surfaces. The new implementation of the cut-cell method



for dynamic end energy balance processes was recently added to the PALM model system. Because this method is relatively new and still being tested, we used the standard model grid in the present simulations.

Another challenge was the line of parked cars on Legerova Street, which directly precedes the observation point L-W from the south (see Fig. 11d). The influence of this barrier was modelled using the Traffic model as a lane of very slowly moving cars. Although this approach is natural, its side effect is that the simulation without the Traffic model did not include the impact of these cars, which likely affected the comparison. A possible solution could be to model cars as obstacles (“building”) using the USM model, which could avoid this drawback. The reason why this approach was not used in the presented simulations is that USM uses the standard grid discretisation (except when employing the cut-cell method), while the Traffic model utilises the fractional approach. Using the USM-modelled obstacles to represent relatively small objects could lead to a large discretisation error, especially in the NO₂ domain.

An important part of the simulation uncertainties stems from the input data, as traffic intensity and speed are crucial inputs. Current construction work and related traffic restrictions on Sokolská Street near the observation area significantly modified also transportation patterns of the surrounding streets (see Section 4.1). This effect was not included in the Traffic model input data preprocessing, likely resulting in overestimated traffic intensities on streets around the Legerova hot spot. Moreover, limitations of the camera record of the traffic situation in Legerova and Sokolska streets used for estimation of the traffic flow in observation areas (see Sect. 4.4.2) caused that some cars could be missed or double-counted. It also caused that split of the car intensity into traffic lines in the Legerova street was not feasible and the split was done by an expertly set fixed ratio. The exception is Sokolská Street, where we obtained a permit to place the camera on top of the building container on 18 June 2026; the dataset from this count is highly reliable.

Uncertainty in meteorological conditions can significantly affect the simulated quantities. Although the LES model can improve the detailed spatio-temporal structure of meteorological quantities, it cannot correct significant deviations in the boundary conditions, as shown, e.g., in Radović et al. (2024). For the 2026 simulations presented, neither the ERA reanalysis nor the regional ALADIN reanalysis were yet available. We used the operational analysis and the first five-hour predictions from the ALADIN system (see Sect. 4.3), which likely represent the best available source for these data in the region. Despite this, the real speed and mainly the direction of the wind at a particular time differ between the model and reality (see the comparison for the meteorological station Prague 2-Karlov (PIPKAR01) in Fig. A5). This can cause different primary vortex creation or other wind structures in the street canyons, which can, in specific localities, significantly influence the results. Fig. A5 also shows that the observed wind speed and especially the direction at the station vary rapidly, often even within a one-hour interval, which cannot be captured by the 1-hour interval of ALADIN outputs. These fluctuations can be responsible for some of the half-hour fluctuations visible in observations, mainly in TKE (see Fig. 7).

6.2 Traffic model limitations

The evaluation shows that including the Traffic model in the PALM model system significantly alters the modelled wind speed, direction, and TKE at the 1 m resolution and typically brings the modelled values closer to observations. The results from the 4 m resolution domain (see Sect. 5.1 and Fig. 3) show that the contribution of the Traffic model at this resolution is lower in all



displayed quantities. This is because the grid size becomes comparable to or larger than typical car dimensions, so important parts of the car effects become subgrid-scale. The current version adds only resolved advection tendencies produced by cars and relies on the LES model turbulent closure to calculate the subgrid-scale tendencies. Thus, the grid resolution must resolve the dimensions of the cars, at least $\Delta_x \sim L_{\text{car}}$; if this condition is not fulfilled, this version of the model will not fully generate subgrid-scale turbulence.

The graphs of TKE_h in Fig. 7 show that while TKE_h is fully restored in the S-W and S-E locations, it remains slightly underestimated in the L-W location during the morning hours. In addition to the factors discussed in Sec. 6.1, another contributing factor can be the fact that the aligned part of the meteorology-induced flow, as modelled in the simulation *eval2-n* without the Traffic model, is oriented against the direction of the cars in the S-W and S-E locations, while it goes in the direction of the cars in L-W most of the day. This can contribute to shear in the first case while partially suppressing it in the second. Moreover, in the model, airflow passes through the car, whereas in reality it flows around it. Besides momentum, this also creates additional turbulence in the wake.

To address this phenomenon, the Traffic model could also influence the subgrid stresses and fluxes based on subgrid characteristics of the traffic stream inside a grid cell. When using the Deardorff SGS model based on the subgrid TKE, the terms of the subgrid TKE equation could be modified to account for the unresolved turbulence production and dissipation. However, the validity of the eddy viscosity assumption and the specific relationship between the subgrid TKE and the eddy viscosity remain unclear and these questions warrant further investigation. This study did not modify the subgrid closure; it used the standard PALM Deardorff SGS model implementation.

Another simplification of the model lies in the fact that one value of the drag coefficient is used to calculate the tendencies in all car orientations relative to the air flow. In reality, the drag coefficients in other orientations differ from the value of the front-side drag coefficient but their values are usually unknown in practice. However, the components of the drag force that act sideways or vertically are typically an order of magnitude smaller than the component along the car's main axis. This simplification thus has a very low impact on the simulated results.

The Traffic model currently parameterises the car flow based on traffic intensity and speed. The speed instability is derived from the speed standard deviation parameter. It does not account for the influence of traffic lights at intersections, which perturb traffic over longer intervals. This may lead to an underestimation of the selected low frequencies in the resulting spectra of TKE (see Fig. 8). This phenomenon deserves further examination.

6.3 Complex impact of the Traffic model

As demonstrated in the previous text, the inclusion of the dynamic and thermal forcing produced by cars typically leads to increased street-canyon ventilation and decreased concentrations of pollutants from local sources. However, this effect is not straightforward, and the impact of these processes can be complex. It can be demonstrated on episode *s6* at times from 19:00 to 22:00 UTC. Fig. 9c shows that the modelled concentrations of PM_{10} in setups *s6-n* and *s6-h* are lower than in setups *s6-t* and *s6-d* in the area of the ALEG measurement station. A similar situation can be observed during the morning hours between 6:00 and 12:00 UTC. The reason for this behaviour can be identified in Fig. A8. The direction of the wind over the roofs is



550 south–west. This configuration, combined with the open area located south–west of the station, induces a helical vortex in the street canyon (Fig. A8c,e), which transports clean air from the open area to the location of the station and transports the local vehicle emissions to the opposite side of the street canyon (Fig. A8a). Vehicle-induced dynamical forcing disturbs this helical vortex, and the major pollutant transfer is oriented in the direction of the traffic stream (Fig. A8d,f). This causes more pollutants to remain in the street canyon. This example shows the complexity of the impacts of traffic-induced processes on air flow and, consequently, air quality in the street canyon. This should be taken into account in practical applications, for example in urban planning.

7 Conclusions

The new Traffic model version 2.0 has been developed and integrated into the PALM model system 26.10. It parametrises the effects of car-induced air flow and heat in terms of the PALM model tendencies of air advection and potential temperature based on input data typically available for traffic emission modelling. The evaluation of the model showed a significant impact on the street canyon turbulent air flow. The influence on the potential temperature was significant during the early morning stable situation and moderate in the convective situation during the day. The comparison with measurements from the real urban observation campaign showed that the application of the model typically brings the simulation results closer to the observations. The agreement between the simulated and observed values was good in the 1 m resolution domain while it was lower in the 4 m resolution domain. The impact on air quality simulation was tested in a simulation replicating a stable low-wind winter situation (episode studied in detail in Resler et al. (2024)). The results demonstrated a significant complex impact of the Traffic model on the PM_{10} concentrations modifying both their magnitude and spatial distribution.

Code and data availability. The Traffic model is distributed as part of the PALM modelling system which is available at https://gitlab.palm-model.org/releases/palm_model_system/-/releases (PALM-model, 2026) under GNU General Public License version 3 or later. This distribution also contains complete documentation of the model. The exact code used for simulations published in this work and Traffic model related parts of the documentation are available on the Zenodo repository under DOI at <https://doi.org/10.5281/zenodo.22831865> (Resler et al., 2026). The input data, observation data, and model configurations needed for replication of this study are available in the same repository at <https://doi.org/10.5281/zenodo.22831865> (Resler et al., 2026).



Appendix A

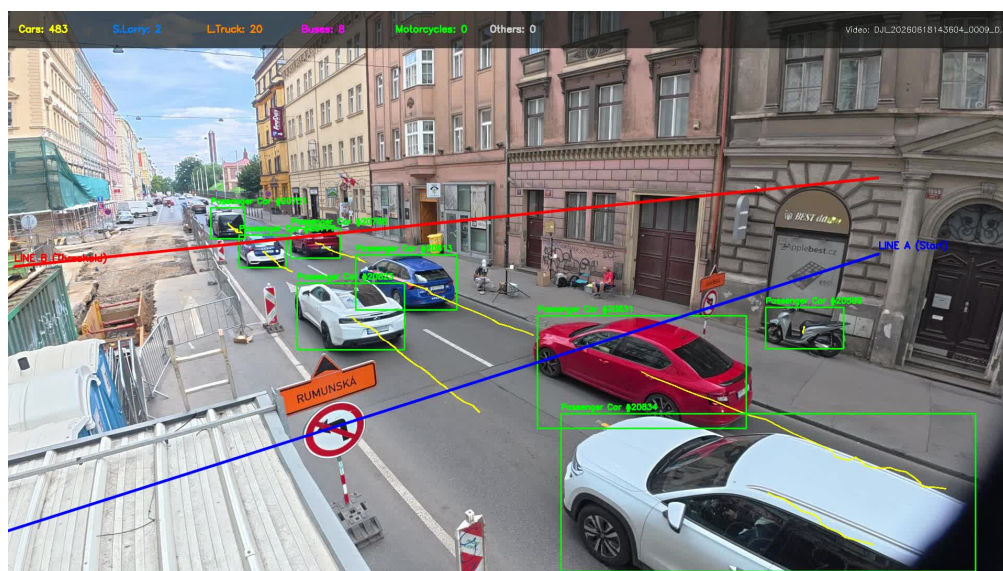


Figure A1. Example of the car counting process from the camera record of the traffic in the Sokolská Street. This view was taken from the building block roof in the south direction.

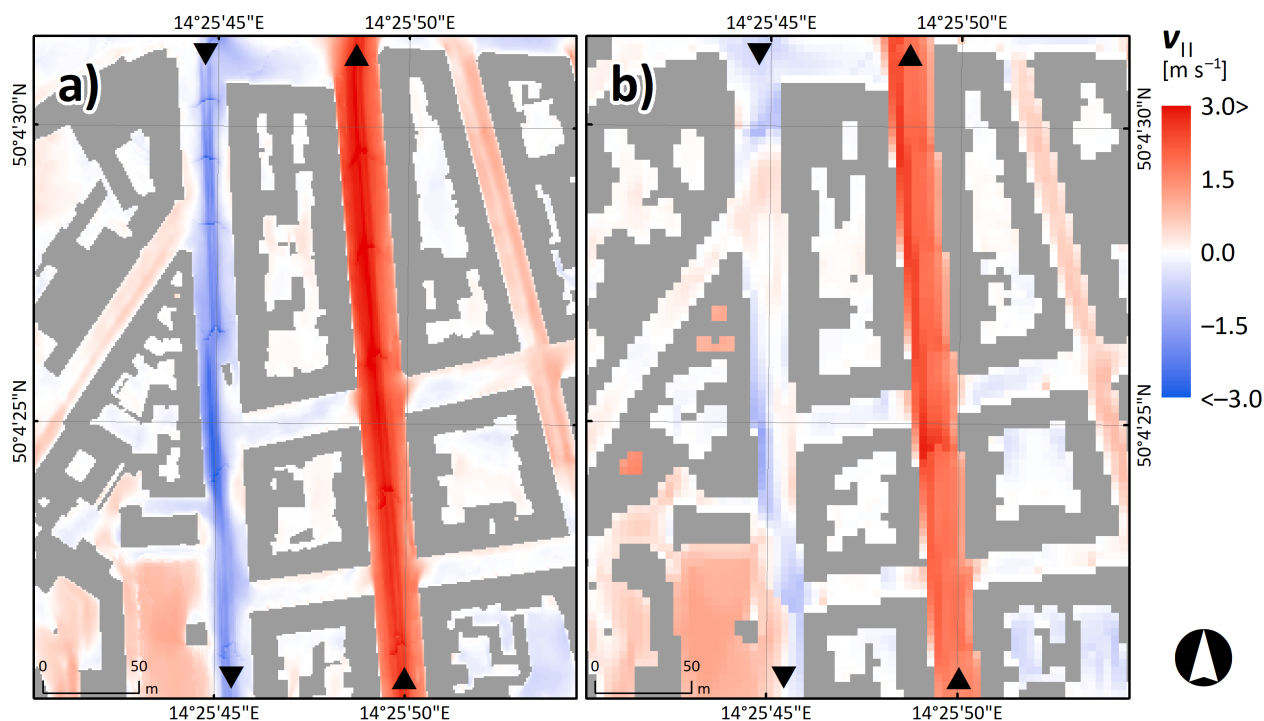


Figure A2. Comparison of the simulated wind component $v_{||}$ in 1 m (a) and 4 m (b) domains with the enabled Traffic model (*eval2-t*). Values represent 10-minute averages on 13 February 2023 between 09:40 and 09:50 UTC at a height of 2 m over the surface. Black triangles indicate traffic direction: north-to-south in Sokolská and south-to-north in Legerova.

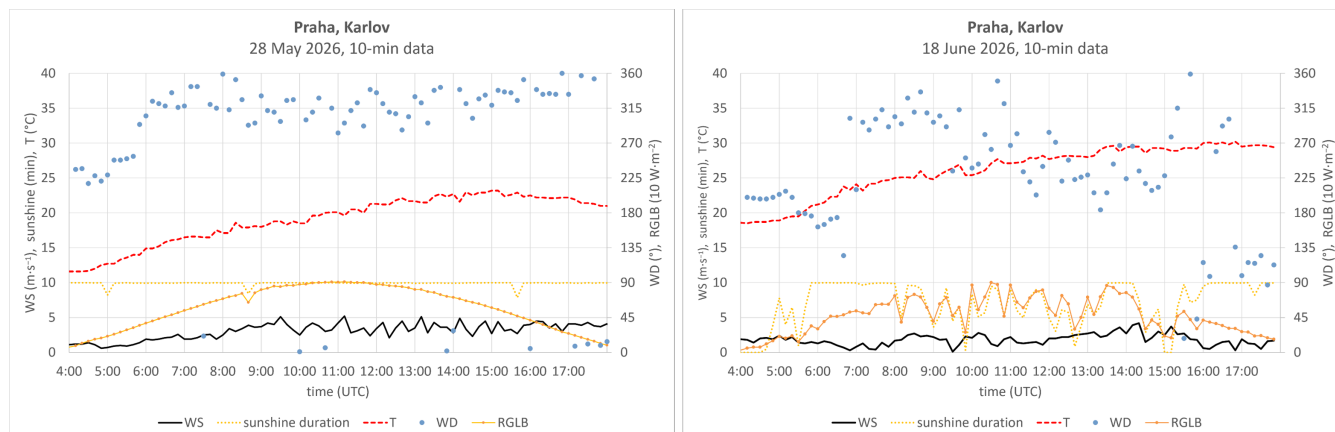


Figure A3. Meteorological conditions at Prague 2-Karlov (PIPKAR01) station on the days of the measurement campaign. WS and WD mean wind speed and direction, T temperature and RGLB global radiation.

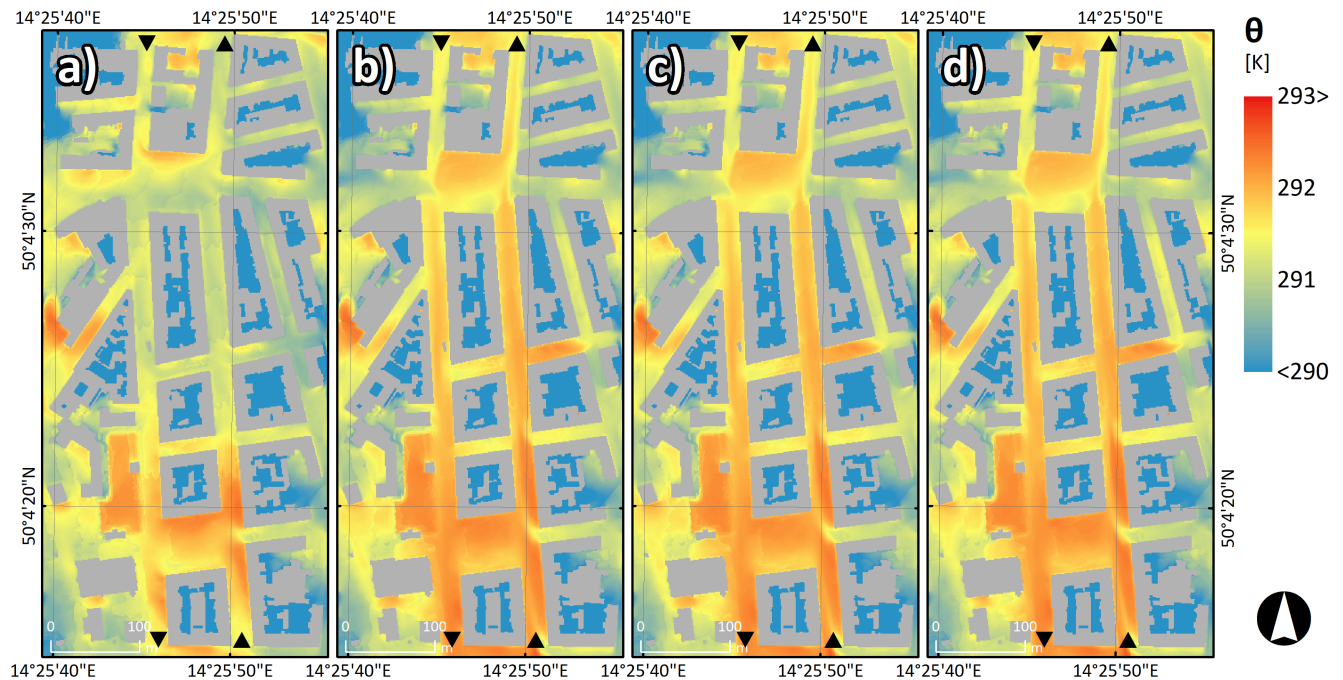


Figure A4. Influence of the Traffic model on the hourly-averaged potential temperature θ at level 2.0 m (averaged layers 2 and 3) from 04:00 to 05:00 UTC. Configuration (a) is *eval2-n* with the Traffic model disabled, (b) Configuration *eval2-t* – Traffic model in default setting, (c) Configuration *eval2-s* – Traffic model with disabled modelling of stream speed instability, and (d) Configuration *eval2-c* – Traffic model with continuous tendency application and disabled simulation of stream speed instability. Detailed description of the configurations is given at the beginning of Sect. 5.1. Black triangles indicate traffic direction: north-to-south in Sokolská and south-to-north in Legerova.



Figure A5. Comparison of the measured and modelled wind speed and direction at Prague 2-Karlov (P1PKAR01) station and the corresponding grid boxes in the models on the day of the second measurement campaign. The black line shows observations, the blue line modelled values from the ALADIN system transformed into PALM parent grid by PALM-meteo tool, and the red line values from the parent PALM domain.

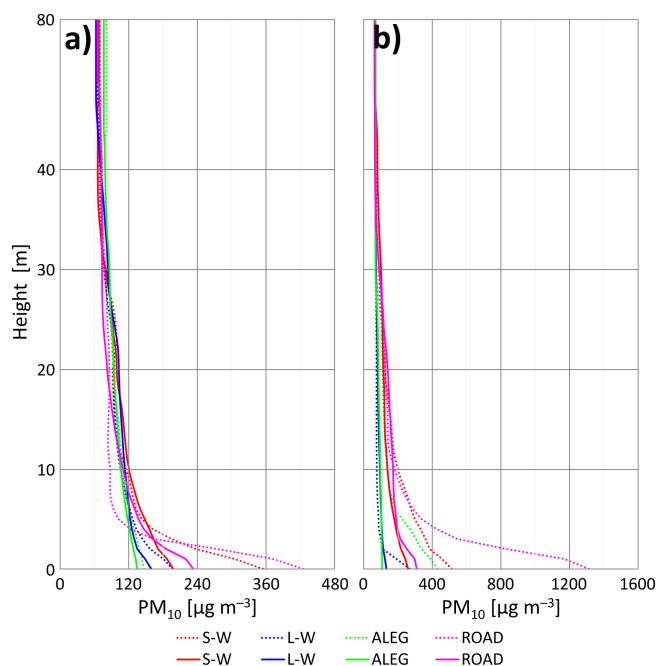


Figure A6. Comparison of the vertical profile of concentrations of PM₁₀ on 13 February 2023 at 07:20 UTC (a) and 17:20 UTC (b) on observation location S-W (red), observation location L-W (blue), monitoring station ALEG (green), and selected hot spot point at the crossroad of the streets Sokolská and Na Bojišti (ROAD; approximately 80 m north from the location S-W). The dotted lines show results simulated with the *s6-n* setup, and the solid lines show results with the *s6-t* setup.

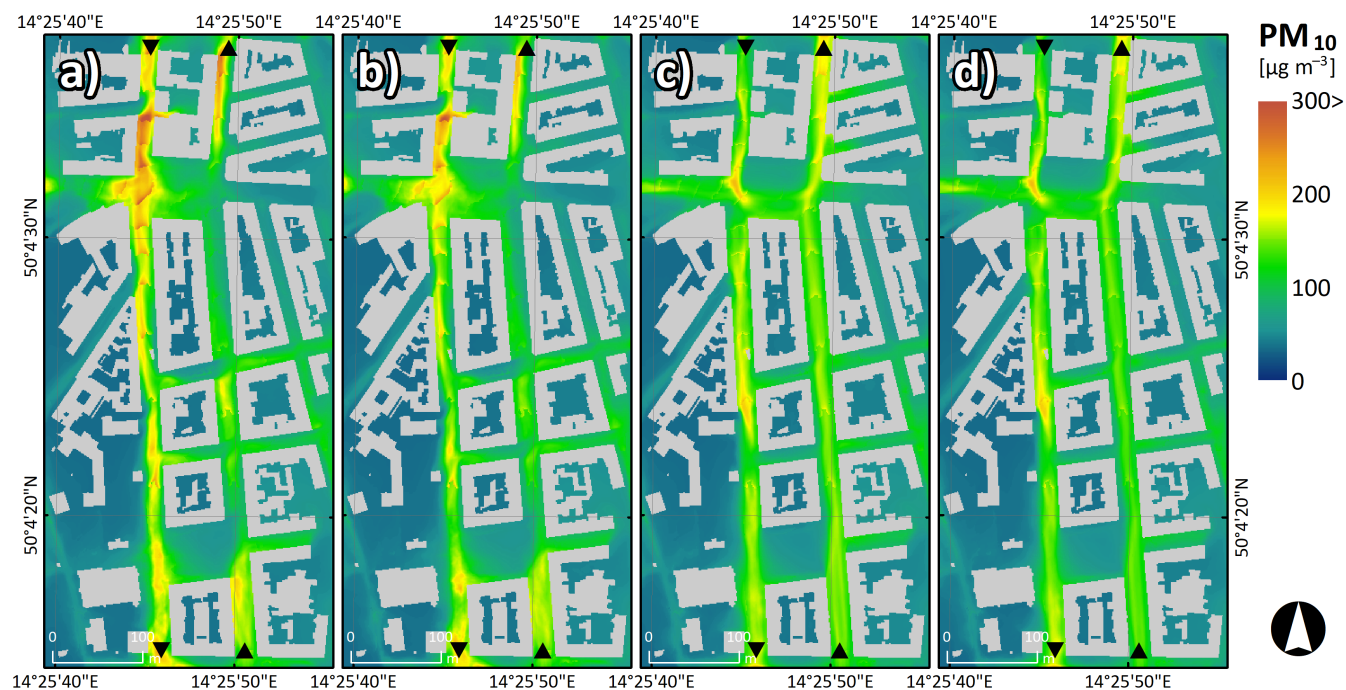


Figure A7. Simulated hourly-averaged concentrations of PM_{10} in the domain N03 at level 2.0 m (averaged layers 2 and 3) on 13 February 2023 for the period 06–07 UTC. Results corresponds to the *s6-n* (a), *s6-h* (b), *s6-d* (c), and *s6-t* (d) setups. Black triangles indicate traffic direction: north-to-south in Sokolská and south-to-north in Legerova.

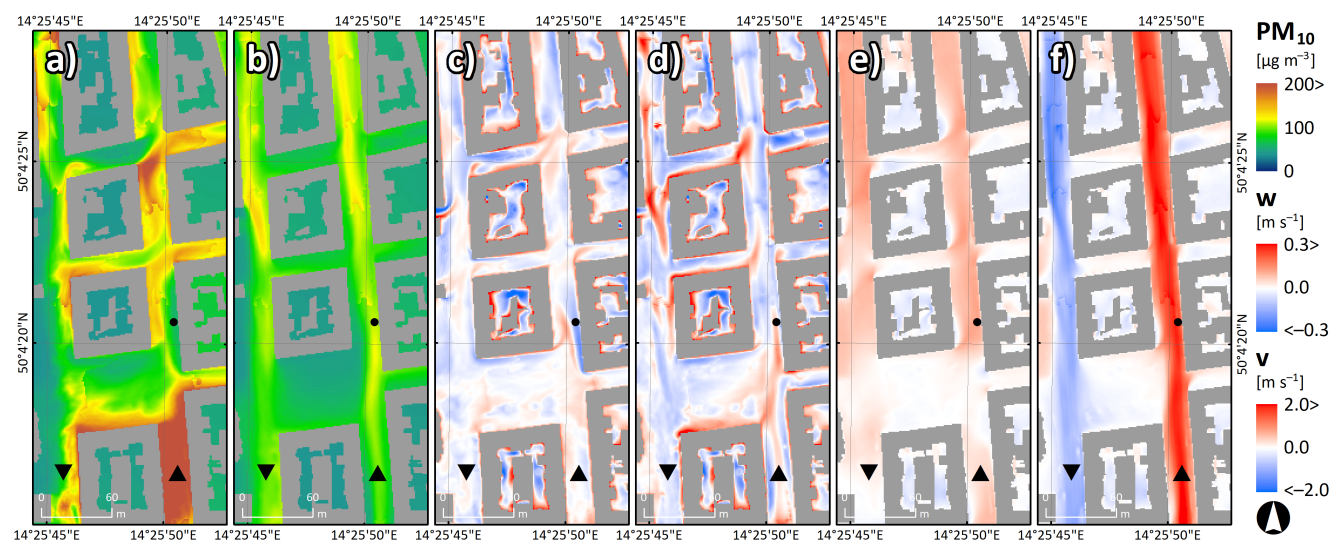


Figure A8. Simulated hourly-averaged concentrations of PM_{10} (maps a and b) and vertical (c and d) and horizontal (e and f) components of the wind velocity at level 3.5 m in the area of the automatic monitoring station ALEG (black point) on 13 February 2023 for the period 19–20 UTC. Results correspond to the setup *s6-n* for maps a, c, and e and *s6-t* for b, d, and f. The black triangles indicate traffic direction.



575 *Author contributions.* J. Resler: Conceptualisation, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project
administration, Supervision, Software, Validation, Visualisation, Writing – original draft, Writing – review and editing. M. Belda: Data cura-
tion, Formal analysis, Investigation, Methodology, Software, Writing – original draft, Writing - Review & Editing. M. Bureš: Data curation,
Validation, Visualisation. K. Eben: Data curation, Validation. Writing – review & editing. V. Fuka: Conceptualisation, Methodology, Writing
- Review & Editing. J. Geletič: Data curation, Formal analysis, Investigation, Validation, Visualisation, Writing – original draft, Writing
580 – review & editing. J. Keder: Data curation, Methodology, Writing - Review & Editing. P. Krč: Conceptualisation, Data curation, Formal
analysis, Funding acquisition, Software, Validation, Writing – review & editing. V. Květoňová: Data curation, Investigation, Writing – review
& editing. T. Pikousová: Data curation, Methodology, Visualisation, Writing – review & editing. J. Radović: Data curation, Methodology,
Writing - Review & Editing. H. Řezníček: Conceptualisation, Data curation, Investigation, Validation, Visualisation, Writing – original
draft, Writing – review & editing. P. Tesařová: Data curation, Methodology, Writing - Review & Editing. O. Vlček: Conceptualisation, Data
585 curation, Investigation, Methodology, Project administration, Validation, Visualisation, Writing – original draft, Writing - Review & Editing.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was supported by the ERDF-Project No. CZ.02.01.01/00/22_008/0004605, Natural and anthropogenic georisks
from the Johannes Amos Comenius Programme (P JAC), and by the MICROBUS project (SQ01010181), which was financed from the state
budget by the Technology Agency of the Czech Republic and the Ministry of the Environment within the “Prostředí pro život 2” Programme.
590 The observation campaign was supported by the project Strategy AV21 Dynamic Planet Earth. The PALM simulations were performed on
the HPC infrastructure of the Institute of Computer Science (ICS) of the Czech Academy of Sciences, supported by the ICS long-term
strategic development financing (RVO 67985807), on the HPC infrastructure of the Czech Hydrometeorological Institute, and on the HPC
infrastructure of the IT4I supercomputing centre supported by the Ministry of Education, Youth and Sports of the Czech Republic through
the e-INFRA CZ (ID no. 90254).
595 We would like to acknowledge our colleagues who carried out the measurements during the observation campaign but are not authors of
this article: Kateřina Kolková, Aleš Létal, Dominik Novotný, Michal Urban, Adéla Žažová (Palacký University Olomouc), and Petr Vincenc
(Czech Hydrometeorological Institute).



References

- Alonso-Estébanez, A., Pascual-Muñoz, P., Yagiüe, C., Laina, R., and Castro-Fresno, D.: Field experimental study of traffic-induced turbulence
600 on highways, *Atmospheric Environment*, 61, 189–196, <https://doi.org/10.1016/j.atmosenv.2012.07.032>, 2012.
- Baik, J.-J. and Kim, J.-J.: A Numerical Study of Flow and Pollutant Dispersion Characteristics in Urban Street Canyons, *J. of Applied Meteorology*, 38, 1576–1589, [https://doi.org/10.1175/1520-0450\(1999\)038<1576:ANSOFA>2.0.CO;2](https://doi.org/10.1175/1520-0450(1999)038<1576:ANSOFA>2.0.CO;2), 1999.
- Baker, C. J. and Hargreaves, D. M.: Wind Tunnel Evaluation of a Vehicle Pollution Dispersion Model, *J. of Wind Engineering and Industrial Aerodynamics*, 89, 187–200, [https://doi.org/10.1016/S0167-6105\(00\)00061-1](https://doi.org/10.1016/S0167-6105(00)00061-1), 2001.
- 605 Bauerová, P., Keder, J., Šindelářová, A., Vlček, O., Patiño, W., Krč, P., Geletič, J., Řezníček, H., Bureš, M., Eben, K., Belda, M., Radović, J., Fuka, V., Jareš, R., Esau, I., and Resler, J.: Measurement report: A complex street-level air quality observation campaign in a heavy-traffic area utilizing the multivariate adaptive regression splines method for field calibration of low-cost sensors, *Atmospheric Chemistry and Physics*, 25, 4477–4504, <https://doi.org/10.5194/acp-25-4477-2025>, 2025.
- Belda, M., Benešová, N., Resler, J., Huszár, P., Vlček, O., Krč, P., Karlický, J., Juruš, P., and Eben, K.: FUME 2.0–Flexible Universal
610 processor for Modeling Emissions, *Geoscientific Model Development*, 17, 3867–3878, <https://doi.org/10.5194/gmd-17-3867-2024>, 2024.
- Bhautmage, U. and Gokhale, S.: Effects of moving-vehicle wakes on pollutant dispersion inside a highway road tunnel, *Environmental pollution*, 218, 783–793, <https://doi.org/10.1016/j.envpol.2016.08.002>, 2016.
- Brožková, R., Mašek, J., Smolíková, P., and Trojáková, A.: New high-resolution operational configuration of the ALADIN model, *Meteorological bulletin*, 72, 129–139, 2019.
- 615 Bureš, M., Geletič, J., Krč, P., and Resler, J.: PALM-GeM: Geospatial Data Merging and Preprocessing into PALM, <https://github.com/PALM-tools/palmgem>, last accessed 27 August 2026, 2026.
- Cai, C., Ming, T., Fang, W., de Richter, R., and Peng, C.: The Effect of Turbulence Induced by Different Kinds of Moving Vehicles in Street Canyons, *Sustainable Cities and Society*, 54, 102 015, <https://doi.org/10.1016/j.scs.2020.102015>, 2020.
- Carpentieri, M., Kumar, P., and Robins, A.: Wind Tunnel Measurements for Dispersion Modelling of Vehicle Wakes, *Atmospheric Environ-*
620 *ment*, 62, 9–25, <https://doi.org/10.1016/j.atmosenv.2012.08.019>, 2012.
- Chang, C.-H. and Meroney, R. N.: Concentration and Flow Distribution in Urban Street Canyons: Wind Tunnel and Computational Data, *J. of Wind Engineering and Industrial Aerodynamics*, 91, 1141–1154, [https://doi.org/10.1016/S0167-6105\(03\)00056-4](https://doi.org/10.1016/S0167-6105(03)00056-4), 2003.
- CHMI-Karlov: Description of the automatic observation station (P1PKAR01, WMO 11519), Prague2-Karlov (in Czech), <https://www.chmi.cz/namerena-data/merici-stanice/meteorologicke/p1pkar01-praha-karlov>, last accessed 21 August 2026, 2026.
- 625 CHMI-Legerova: Description of the automatic observation station ALEG, Prague2-Legerova (in Czech), <https://ovzdusi.chmi.cz/lokalita.php?ID=ALEG>, last accessed 21 August 2026, 2026.
- Deardorff, J. W.: Stratocumulus-Capped Mixed Layers Derived from a Three-Dimensional Model, *Boundary-Layer Meteorology*, 18, 495–527, <https://doi.org/10.1007/BF00119502>, 1980.
- DePaul, F. T. and Sheih, C. M.: Measurements of Wind Velocities in a Street Canyon, *Atmospheric Environment*, 20, 455–459, [https://doi.org/10.1016/0004-6981\(86\)90085-5](https://doi.org/10.1016/0004-6981(86)90085-5), 1986.
- 630 Di Sabatino, S., Kastner-Klein, P., Berkowicz, R., Britter, R., and Fedorovich, E.: The Modelling of Turbulence from Traffic in Urban Dispersion Models – Part I: Theoretical Considerations, *Environmental Fluid Mechanics*, 3, 129–143, <https://doi.org/10.1023/A:1022063608237>, 2003.



- Eliasson, I., Offerle, B., Grimmond, C. S. B., and Lindqvist, S.: Wind Fields and Turbulence Statistics in an Urban Street Canyon, *Atmospheric Environment*, 40, 1–16, <https://doi.org/10.1016/j.atmosenv.2005.03.031>, 2006.
- Gehrke, K. F., Sühling, M., and Maronga, B.: Modeling of land–surface interactions in the PALM model system 6.0: land surface model description, first evaluation, and sensitivity to model parameters, *Geoscientific Model Development*, 14, 5307–5329, <https://doi.org/10.5194/gmd-14-5307-2021>, 2021.
- Giard, D. and Bazile, E.: Implementation of a New Assimilation Scheme for Soil and Surface Variables in a Global NWP Model, *Monthly Weather Review*, 128, 997 – 1015, [https://doi.org/10.1175/1520-0493\(2000\)128<0997:IOANAS>2.0.CO;2](https://doi.org/10.1175/1520-0493(2000)128<0997:IOANAS>2.0.CO;2), 2000.
- Gill Instruments Limited: MetConnect THP, Professional Weather Station, User manual, <https://gillinstruments.com/wp-content/uploads/2022/06/1733-PS-0004-MetConnect-Manual-Iss-2.pdf>, 2022.
- Gill Instruments Limited: WindSonic Datasheet, Wind Speed and Direction Sensors, <https://gillinstruments.com/wp-content/uploads/2024/07/1405-027-WindSonic-issue-10.pdf>, 2024.
- Gromke, C. and Ruck, B.: Influence of Trees on the Dispersion of Pollutants in an Urban Street Canyon – Experimental Investigation of the Flow and Concentration Field, *Atmospheric Environment*, 41, 3287–3302, <https://doi.org/10.1016/j.atmosenv.2006.12.043>, 2007.
- Gustafsson, N., Janjić, T., Schraff, C., Leuenberger, D., Weissmann, M., Reich, H., Brousseau, P., Montmerle, T., Wattrelot, E., Bučánek, A., Mile, M., Hamdi, R., Lindskog, M., Barkmeijer, J., Dahlbom, M., Macpherson, B., Ballard, S., Inverarity, G., Carley, J., Alexander, C., Dowell, D., Liu, S., Ikuta, Y., and Fujita, T.: Survey of data assimilation methods for convective-scale numerical weather prediction at operational centres, *Quarterly Journal of the Royal Meteorological Society*, 144, 1218–1256, <https://doi.org/10.1002/qj.3179>, 2018.
- Hashad, K., Yang, B., Iskov, V., and Max Zhang, K.: A computationally efficient approach to resolving vehicle-induced turbulence for near-road air quality, *J. of Engineering for Sustainable Buildings and Cities*, 3, 031 001, <https://doi.org/10.1115/1.4055640>, 2022.
- Hellsten, A., Ketelsen, K., Sühling, M., Auvinen, M., Maronga, B., Knigge, C., Tsegas, F. B. G., Moussiopoulos, N., and Raasch, S.: A Nested Multi-Scale System Implemented in the Large-Eddy Simulation Model PALM Model System 6.0, *Geoscientific Model Development*, 14, 3185–3214, <https://doi.org/10.5194/gmd-14-3185-2021>, 2021.
- Hu, Z. and Noll, K. E.: Near-Road Traffic Emission Dispersion Model: Traffic-Induced Turbulence Kinetic Energy (TKE) Measurement, *Atmosphere*, 14, 1485, <https://doi.org/10.3390/atmos14101485>, 2023.
- Jícha, M. and Pospíšil, J.: Dispersion of Pollutants in a Street Canyon and Street Intersection under Traffic-Induced Flow and Turbulence Using a Low-Re $k-\epsilon$ Model, *International J. of Environment and Pollution*, 18, 160–170, <https://doi.org/10.1504/IJEP.2002.012126>, 2002.
- Jícha, M., Pospíšil, J., and Katolický, J.: Dispersion of Pollutants in Street Canyon under Traffic Induced Flow and Turbulence, *Environmental Monitoring and Assessment*, 18, 343–351, <https://doi.org/10.1023/A:1006452422885>, 2000.
- Jin, X., Yang, L., Du, X., and Yang, Y.: Transport Characteristics of PM_{2.5} inside Urban Street Canyons: The Effects of Trees and Vehicles, *Building Simulation*, 10, 337–350, <https://doi.org/10.1007/s12273-016-0324-1>, 2017.
- Kadasch, E., Sühling, M., Gronemeier, T., and Raasch, S.: Mesoscale nesting interface of the PALM model system 6.0, *Geoscientific Model Development*, 14, 5435–5465, <https://doi.org/10.5194/gmd-14-5435-2021>, 2021.
- Kanda, I., Uehara, K., Yamao, Y., Yoshikawa, Y., and Morikawa, T.: A wind-tunnel study on exhaust gas dispersion from road vehicles—Part I: Velocity and concentration fields behind single vehicles, *J. of wind engineering and industrial aerodynamics*, 94, 639–658, <https://doi.org/10.1016/j.jweia.2005.12.003>, 2006a.
- Kanda, I., Uehara, K., Yamao, Y., Yoshikawa, Y., and Morikawa, T.: A wind-tunnel study on exhaust-gas dispersion from road vehicles—Part II: Effect of vehicle queues, *J. of wind engineering and industrial aerodynamics*, 94, 659–673, <https://doi.org/10.1016/j.jweia.2006.06.002>, 2006b.



- Karttunen, S., Sührling, M., O'Connor, E., and Järvi, L.: PALM-SLUrb v24.04: a single-layer urban canopy model for the PALM model system – model description and first evaluation, *Geoscientific Model Development*, 18, 5725–5757, <https://doi.org/10.5194/gmd-18-5725-2025>, 2025.
- 675 Kastner-Klein, P. and Plate, E. J.: Wind-Tunnel Study of Concentration Fields in Street Canyons, *Atmospheric Environment*, 33, 3973–3979, [https://doi.org/10.1016/S1352-2310\(99\)00139-9](https://doi.org/10.1016/S1352-2310(99)00139-9), 1999.
- Kastner-Klein, P., Berkowicz, R., and Plate, E.: Modelling of vehicle-induced turbulence in air pollution studies for streets, *International J. of Environment and Pollution*, 14, 496–507, <https://doi.org/10.1504/IJEP.2000.000573>, 2000a.
- Kastner-Klein, P., Fedorovich, E., Ois Sini, J., and Mestayer, P.: Experimental and Numerical Verification of Similarity Concept for Dispersion of Car Exhaust Gases in Urban Street Canyons., *Environmental Monitoring and Assessment*, 65, 353–361, <https://doi.org/10.1023/A:1006404507864>, 2000b.
- 680 Kastner-Klein, P., Fedorovich, E., and Rotach, M. W.: A Wind Tunnel Study of Organised and Turbulent Air Motions in Urban Street Canyons, *J. of Wind Engineering and Industrial Aerodynamics*, 89, 849–861, [https://doi.org/10.1016/S0167-6105\(01\)00074-5](https://doi.org/10.1016/S0167-6105(01)00074-5), 2001.
- Kastner-Klein, P., Fedorovich, E., Ketzler, M., Berkowicz, R., and Britter, R.: The modelling of turbulence from traffic in urban dispersion models—Part II: evaluation against laboratory and full-scale concentration measurements in street canyons, *Environmental Fluid Mechanics*, 3, 145–172, <https://doi.org/10.1023/A:1022049224166>, 2003.
- Katolický, J. and Jícha, M.: Eulerian–Lagrangian Model for Traffic Dynamics and Its Impact on Operational Ventilation of Road Tunnels, *J. of Wind Engineering and Industrial Aerodynamics*, 93, 61–77, <https://doi.org/10.1016/j.jweia.2004.09.002>, 2005.
- Khan, B., Banzhaf, S., Chan, E. C., Forkel, R., Kanani-Sührling, F., Ketelsen, K., Kurppa, M., Maronga, B., Mauder, M., Raasch, S., et al.: Development of an atmospheric chemistry model coupled to the PALM model system 6.0: Implementation and first applications, *Geoscientific Model Development*, 14, 1171–1193, <https://doi.org/10.5194/gmd-14-1171-2021>, 2021.
- 690 Kim, Y., Huang, L., Gong, S., and Jia, C.: A New Approach to Quantifying Vehicle Induced Turbulence for Complex Traffic Scenarios, *Chinese J. of Chemical Engineering*, 24, 71–78, <https://doi.org/10.1016/j.cjche.2015.11.025>, 2016.
- Krč, P., Resler, J., Sührling, M., Schubert, S., Salim, M. H., and Fuka, V.: Radiative Transfer Model 3.0 integrated into the PALM model system 6.0, *Geoscientific Model Development*, 14, 3095–3120, <https://doi.org/10.5194/gmd-14-3095-2021>, 2021.
- 695 Krč, P., Belda, M., Bureš, M., Eben, K., Geletič, J., Radović, J., Rezníček, H., and Resler, J.: PALM-meteo 2.8: Processor of PALM meteorological input data, *Geoscientific Model Development*, 19, 4071–4093, <https://doi.org/10.5194/gmd-19-4071-2026>, 2026.
- Li, Z., Xu, J., Ming, T., Peng, C., Huang, J., and Gong, T.: Numerical Simulation on the Effect of Vehicle Movement on Pollutant Dispersion in Urban Street, in: *Procedia Engineering*, vol. 205, pp. 2303–2310, <https://doi.org/10.1016/j.proeng.2017.10.104>, 2017.
- 700 Lo, K. H. and Kontis, K.: Flow around an articulated lorry model, *Experimental Thermal and Fluid Science*, 82, 58–74, <https://doi.org/10.1016/j.expthermflusci.2016.11.003>, 2017.
- Maronga, B., Banzhaf, S., Burmeister, C., Esch, T., Forkel, R., Fröhlich, D., Fuka, V., Gehrke, K. F., Geletič, J., Giersch, S., Gronemeier, T., Gross, G., Heldens, W., Hellsten, A., Hoffmann, F., Inagaki, A., Kadasch, E., Kanani-Sührling, F., Ketelsen, K., Khan, B. A., Knigge, C., Knoop, H., Krč, P., Kurppa, M., Maamari, H., Matzarakis, A., Mauder, M., Pallasch, M., Pavlik, D., Pfaffertrott, J., Resler, J., Rissmann, S., Russo, E., Salim, M., Schrempf, M., Schwenkel, J., Seckmeyer, G., Schubert, S., Sührling, M., von Tils, R., Vollmer, L., Ward, S., Witha, B., Wurps, H., Zeidler, J., and Raasch, S.: Overview of the PALM Model System 6.0, *Geoscientific Model Development*, 13, 1335–1372, <https://doi.org/10.5194/gmd-13-1335-2020>, 2020.



- Miller, S. J.: An Investigation of Turbulence and Diffusion within Vehicle Wakes and On-Road Measurements using an Instrumented Mobile Car and a Stationary Roadside Monitoring System, Ph.D. thesis, Lassonde School Of Engineering, York University, Toronto, Canada, <http://hdl.handle.net/10315/40759>, 2022.
- 710 Miller, S. J., Gordon, M., Staebler, R. M., and Taylor, P. A.: A study of the spatial variation of vehicle-induced turbulence on highways using measurements from a mobile platform, *Boundary Layer Meteorology*, 171, 1–29, <https://doi.org/10.1007/s10546-018-0416-9>, 2019.
- Moeng, C.-H. and Wyngaard, J. C.: Spectral Analysis of Large-Eddy Simulations of the Convective Boundary Layer, *J. of the Atmospheric Sciences*, 45, 3573–3587, [https://doi.org/10.1175/1520-0469\(1988\)045<3573:SAOLES>2.0.CO;2](https://doi.org/10.1175/1520-0469(1988)045<3573:SAOLES>2.0.CO;2), 1988.
- 715 Motisi, G., Gromke, C., Carpentieri, M., and Maronga, B.: Modeling vehicle-induced turbulence in large-eddy simulations: Formulation of a simple method and validation against wind tunnel experiments in an idealized street canyon, *J. of Wind Engineering and Industrial Aerodynamics*, 275, 106 519, <https://doi.org/10.1016/j.jweia.2026.106519>, 2026.
- Nath, D. S., Pujari, P. C., Jain, A., and Rastogi, V.: Drag reduction by application of aerodynamic devices in a race car, *Advances in Aerodynamics*, 3, 4, <https://doi.org/10.1186/s42774-020-00054-7>, 2021.
- 720 Oke, T. R., Mills, G., Christen, A., and Voegt, J. A.: *Urban climates*, Cambridge University Press, <https://doi.org/10.1017/9781139016476>, 2017.
- PALM-model: PALM model system gitlab, <https://gitlab.palm-model.org>, last accessed 27 August 2026, 2026.
- Pospíšil, J. and Jícha, M.: Influence of Vehicle-Induced Turbulence on Pollutant Dispersion in Street Canyon and Adjacent Urban Area, *International J. of Environment and Pollution*, 62, 89–101, <https://doi.org/10.1504/IJEP.2017.089400>, 2017.
- 725 Pospíšil, J. and Jícha, M.: Numerical Modelling of Transient Dispersion of Air Pollution in Perpendicular Urban Street Intersection with Detailed Inclusion of Traffic Dynamics, *International J. of Environment and Pollution*, 65, 71–83, <https://doi.org/10.1504/IJEP.2019.101834>, 2019.
- Qin, Y. and Kot, S. C.: Dispersion of Vehicular Emission in Street Canyons, Guangzhou City, South China (P.R.C.), *Atmospheric Environment Part B*, 27, 283–291, [https://doi.org/10.1016/0957-1272\(93\)90023-Y](https://doi.org/10.1016/0957-1272(93)90023-Y), 1993.
- 730 Radović, J., Belda, M., Resler, J., Eben, K., Bureš, M., Geletič, J., Krč, P., Řezníček, H., and Fuka, V.: Challenges of constructing and selecting the “perfect” boundary conditions for the large-eddy simulation model PALM, *Geoscientific Model Development*, 17, 2901–2927, <https://doi.org/10.5194/gmd-17-2901-2024>, 2024.
- Reinert, D., Prill, F., Frank, H., Denhard, M., Baldauf, M., Schraff, C., Gebhardt, C., Marsigli, C., and Zängl, G.: DWD database reference for the global and regional ICON and ICON-EPS forecasting system, version 2.5.6, https://www.dwd.de/DWD/forschung/nwv/fepub/icon_database_main.pdf, [cited 20.4.2024], 2020.
- 735 Resler, J., Krč, P., Belda, M., Juruš, P., Benešová, N., Lopata, J., Vlček, O., Damašková, D., Eben, K., Derbek, P., Maronga, B., and Kanani-Sühring, F.: PALM-USM v1.0: A New Urban Surface Model Integrated into the PALM Large-Eddy Simulation Model, *Geoscientific Model Development*, 10, 3635–3659, <https://doi.org/10.5194/gmd-10-3635-2017>, 2017.
- Resler, J., Eben, K., Geletič, J., Krč, P., Rosecký, M., Sühring, M., Belda, M., Fuka, V., Halenka, T., Huszár, P., Karlický, J., Benešová, N., Ďoubalová, J., Honzánková, K., Keder, J., Nápravníková, v., and Vlček, O.: Validation of the PALM model system 6.0 in a real urban environment: a case study in Dejvice, Prague, the Czech Republic, *Geoscientific Model Development*, 14, 4797–4842, <https://doi.org/10.5194/gmd-14-4797-2021>, 2021.
- 740 Resler, J., Bauerová, P., Belda, M., Bureš, M., Eben, K., Fuka, V., Geletič, J., Jareš, R., Karel, J., Keder, J., Krč, P., Patiño, W. R., Radović, J., Řezníček, H., Sühring, M., Šindelářová, A., and Vlček, O.: Challenges of high-fidelity air quality modeling in urban environments–PALM



- 745 sensitivity study during stable conditions, *Geoscientific Model Development*, 17, 7513–7537, <https://doi.org/10.5194/gmd-17-7513-2024>, 2024.
- Resler, J., Bauerová, P., Belda, M., Bureš, M., Geletič, J., Eben, K., Keder, J., Květoňová, V., and Vlček, O.: PALM-Traffic 2.0: Implementation of the traffic-induced heat and velocity in the PALM model system [dataset], <https://doi.org/10.5281/zenodo.22831865>, last accessed 18 September 2026, 2026.
- 750 Sahlodin, A., Sotudeh-Gharebagh, R., and Zhu, Y.: Modeling of Dispersion Near Roadways Based on the Vehicle-Induced Turbulence Concept, *Atmospheric Environment*, 41, 92–102, <https://doi.org/10.1016/j.atmosenv.2006.08.004>, 2007.
- Saiki, E. M., Moeng, C.-H., and Sullivan, P. P.: Large-Eddy Simulation of the Stably Stratified Planetary Boundary Layer, *Boundary-Layer Meteorology*, 95, 1–30, <https://doi.org/10.1023/A:1002428223156>, 2000.
- Shi, X., Sun, D., Fu, S., Zhao, Z., and Liu, J.: Assessing on-road emission flow pattern under car-following induced turbulence using computational fluid dynamics (CFD) numerical simulation, *Sustainability*, 11, 6705, <https://doi.org/10.3390/su11236705>, 2019.
- 755 So, E. S. P., Chan, A. T. Y., and Wong, A. Y. T.: Large-Eddy Simulations of Wind Flow and Pollutant Dispersion in a Street Canyon, *Atmospheric Environment*, 39, 3573–3582, <https://doi.org/10.1016/j.atmosenv.2005.02.044>, 2005.
- Solazzo, E., Vardoulakis, S., and Cai, X.: Evaluation of Traffic-Producing Turbulence Schemes Within Operational Street Pollution Models Using Roadside Measurements, *Atmospheric Environment*, 41, 5357–5370, <https://doi.org/10.1016/j.atmosenv.2007.02.017>, 2007.
- 760 Sun, Y., Oleson, K. W., and Zheng, Z.: Modeling urban traffic heat flux in the Community Earth System Model: Formulation and validation for two test sites, *Journal of Advances in Modeling Earth Systems*, 18, e2025MS005435, <https://doi.org/10.1029/2025MS005435>, 2026.
- Termonia, P., Fischer, C., Bazile, E., Bouyssel, F., Brožková, R., Bénard, P., Bochenek, B., Degrauwe, D., Derková, M., El Khatib, R., Hamdi, R., Mašek, J., Pottier, P., Pristov, N., Seity, Y., Smolíková, P., Španiel, O., Tudor, M., Wang, Y., Wittmann, C., and Joly, A.: The ALADIN System and its canonical model configurations AROME CY41T1 and ALARO CY40T1, *Geoscientific Model Development*, 11, 257–281, <https://doi.org/10.5194/gmd-11-257-2018>, 2018.
- 765 Thaker, P. and Gokhale, S.: The impact of traffic-flow patterns on air quality in urban street canyons, *Environmental pollution*, 208, 161–169, <https://doi.org/10.1016/j.envpol.2015.09.004>, 2016.
- Wang, Q., Fang, W., et al.: Effect of Moving Vehicles on Pollutant Dispersion in Street Canyon by Using Dynamic Mesh Updating Method, *J. of Wind Engineering and Industrial Aerodynamics*, 187, 15–25, <https://doi.org/10.1016/j.jweia.2019.01.014>, 2019.
- 770 Wang, Y. J. and Zhang, K. M.: Coupled turbulence and aerosol dynamics modeling of vehicle exhaust plumes using the CTAG model, *Atmospheric Environment*, 59, 284–293, <https://doi.org/10.1016/j.atmosenv.2012.04.062>, 2012.
- Wicker, L. J. and Skamarock, W. C.: Time-Splitting Methods for Elastic Models Using Forward Time Schemes, *Monthly Weather Review*, 130, 2088–2097, [https://doi.org/10.1175/1520-0493\(2002\)130<2088:TSMFEM>2.0.CO;2](https://doi.org/10.1175/1520-0493(2002)130<2088:TSMFEM>2.0.CO;2), 2002.
- Williamson, J. H.: Low-Storage Runge–Kutta Schemes, *J. of Computational Physics*, 35, 48–56, [https://doi.org/10.1016/0021-9991\(80\)90033-9](https://doi.org/10.1016/0021-9991(80)90033-9), 1980.
- 775 Woodward, H., Stettler, M. E. J., Pavlidis, D., Aristodemou, E., ApSimon, H., and Pain, C.: A Large Eddy Simulation of the Dispersion of Traffic Emissions by Moving Vehicles at an Intersection, *Atmospheric Environment*, 215, 116891, <https://doi.org/10.1016/j.atmosenv.2019.116891>, 2019.
- World Health Organization: Ambient (outdoor) air pollution, [https://www.who.int/news-room/fact-sheets/detail/ambient-\(outdoor\)-air-quality-and-health](https://www.who.int/news-room/fact-sheets/detail/ambient-(outdoor)-air-quality-and-health), last accessed 21 September 2026, 2024.
- 780 World Meteorological Organization: Guidance on Integrated Urban Hydrometeorological, Climate and Environment Services, World Meteorological Organization, ISBN 978-92-63-11234-7, <https://library.wmo.int/viewer/57316>, 2021.



- Zhang, K. and Batterman, S.: Air pollution and health risks due to vehicle traffic, *Science of the total Environment*, 450, 307–316, <https://doi.org/10.1016/j.scitotenv.2013.01.074>, 2013.
- 785 Zhang, Y., Gu, Z., and Yu, C. W.: Large Eddy Simulation of Vehicle Induced Turbulence in an Urban Street Canyon with a New Dynamically Vehicle-Tracking Scheme, *Aerosol and Air Quality Research*, 17, 865–874, <https://doi.org/10.4209/aaqr.2016.05.0204>, 2017.
- Zhang, Y., Wen, L., Zhang, X., Fu, Y., Tse, T., and Mak, C.: Enhanced Modeling of Vehicle-Induced Turbulence and Pollutant Dispersion in Urban Street Canyon: Large-Eddy Simulation via Dynamic Overset Mesh Approach, *Sustainable Cities and Society*, 117, 105 939, <https://doi.org/10.1016/j.scs.2024.105939>, 2024.
- 790 Zheng, X. and Yang, J.: CFD Simulations of Wind Flow and Pollutant Dispersion in a Street Canyon with Traffic Flow: Comparison Between RANS and LES, *Sustainable Cities and Society*, 75, 103 307, <https://doi.org/10.1016/j.scs.2021.103307>, 2021.
- Zheng, X. and Yang, J.: Impact of Moving Traffic on Pollutant Transport in Street Canyons Under Perpendicular Winds: A CFD Analysis Using Large-Eddy Simulations, *Sustainable Cities and Society*, 82, 103 911, <https://doi.org/10.1016/j.scs.2022.103911>, 2022.