ABSTRACT: In this paper wind tunnel dispersion tests and accompanying numerical simulations of the planned north section of the Budapest ring motorway M0 are reported. The investigated suburban area is located between hills and several tunnels and viaducts are planned. Wind tunnel tests were carried out on a 1:1000 scale model containing topography, buildings and vegetation in a Göttingen-type wind tunnel. Road segments were modeled as line sources, tunnel portals as point sources with horizontal momentum. Concentrations were measured in 50 sampling points. Numerical simulations of the same case were performed using the MISKAM code. Using both methods, large pollutant plumes near tunnel portals were observed, reaching also populated areas far from the motorway. In consequence, extension of the tunnel ventilation system by ventilation stacks was proposed. Effect of the stacks was proven numerically.

1 INTRODUCTION

The planned section of the ring motorway M0 in the north of Budapest is about 9km long, connecting national roads 10 and 11 and consisting of 3 junctions. As the motorway will run close to populated urban and suburban areas, an extensive wind tunnel test was initiated by the National Infrastructural Development Corporation, to react on the public pressure from local and environmental groups.

All of the investigated road variants (Fig. 1) run in complex terrain of Buda Mountain and include several bridges and tunnels. The area of investigation covers about 8×5 km.

Wind tunnel studies of highway projects are common in wind engineering. However, in this case specific attention had to be paid to the flow over complex terrain and to the dispersion from tunnel portals.

Complex terrain can produce a variety of flow patterns, mainly depending on the topography and the thermal stratification (Froude number), as it is described in standard texts, e.g. Plate [1]. An overview of research in the last 50 years is given by Wood [2]. Besides numerous studies about isolated 2D or 3D hills, wind tunnel tests of real-world terrain were performed e.g. by Cermak [3] for different stratifications. However, most environmental wind tunnels can model only neutral conditions. Application focus of the studies in this field is also on heavy gas dispersion, wind turbine siting and the determination of airport wind conditions.

In roadway tunnels large amount of traffic pollution can be accumulated, which is removed by the pressure difference, the piston effect of moving vehicles and the tunnel ventilation system mostly through the tunnel portal. An overview of tunnel related air quality problems is given by Longley and Kelly [4] and Bettelini et al. [5], the latter showing also modeling results near a tunnel portal with a Gaussian model and CFD. Oettl et al. [6] compared results from two specific portal dispersion models with on-site measurements.

Wind tunnel measurements of a tunnel portal with moving vehicles were reported by Nadel et al. [7] and Plate [8]. They observed high concentrations near the portal and recognized the
influence of traffic induced turbulence. Contini et al. [9] measured flow and dispersion near tunnel portals behind a 2D hill. Tunnel emissions were released from a point source at the portal.

Tunnel ventilation systems are designed according national standards like that of Switzerland [10]. To avoid large concentrations near the portals of longer tunnels, separate ventilation stacks or filter facilities have to be installed. The original design of the planned one-directional tunnels in Budapest included longitudinal ventilation using axial fans without any ventilation stack.

![Figure 1](image)

**Figure 1.** The investigated domain with existing main roads and planned road variants 1, 3, 3.1 and 6. Dots: wind tunnel sampling points; dashed line: inhabited area

### 2  INPUT DATA

Unlike in scientific investigations, which are mainly focused on the dispersion phenomena, at the end of environmental impact assessment studies, exact concentrations should be calculated as a decision basis and transmitted to the authorities. Any errors in input data like in wind statistics or car emissions will be reflected also in the results. Thus one has to pay specific attention to the collection of high-quality input data.

Car emissions can be determined from traffic density and from the emission factors of different vehicle categories. These are again dependent from fleet composition, traffic situation, slope, etc. In this project, emission factors for the reference year 2006 and realization year 2018 were determined from fleet composition data of the Hungarian Central Statistical Office and from the Handbook of Emission Factors [11]. This latter is the database of the DACH countries, that was already validated e.g. by tunnel measurements of Colberg et al. [12].

Long-term wind statistics were only available at a station of the Hungarian Meteorological Service about 5 km from the site in a flat area. To determine local wind statistics, the diagnostic wind field model DIWIMO (Moussiopoulos [13]) was run on a 38×16 km domain by a partner company. In the simulation, effects of topography, stratification, varying surface roughness and coverage were accounted for. The generated wind roses show higher average wind speed and distortions due to topographic effects (Fig. 2). In Junction 3, influence of a
NW-SE valley can be clearly recognized. Based on the results, 5 incident wind directions were selected in each junction for further investigation, covering about 80% of the year.

Figure 2: Left: domain of DIWIMO simulation; right: original and generated wind roses, simplified for 8 wind directions

3 WIND TUNNEL TESTS

The test section of the Göttingen-type wind tunnel had to be modified to accommodate the oversized model, meaning that part of the model reached into the outlet diffuser (Fig. 3). Hence the pressure gradient was checked (Fig. 4, right) and values of \( \frac{\Delta c_p}{\Delta x \cdot \delta} \) (with pressure coefficient \( c_p = \frac{\Delta p_{stat}}{p_{dyn}} \)) below \( \pm 5\% \) were found, fulfilling the requirement set in the VDI guideline [14].

The neutral atmospheric boundary layer profile was modeled by a horizontal grid, spikes and roughness elements (Fig. 5) and was checked by 2-component hot-wire measurements (cross-wire sensor with DISA 55M CTA bridges). Results are shown in Fig. 4 on the left.

The measurements were carried out on a 1:1000 scale model of 28.5m² total area, consisting of 62 modules and resolving the topography, buildings, vegetation and pollutant sources of the surroundings (Fig. 6). From the modules, models of the 3 junctions at various wind directions and road variants could be constructed and investigated separately. The model had a certain roughness due to the textile map laminated on its surface. The elevation at the model boundary was relaxed to zero level using artificial slopes.

50 sampling points were distributed on the model (Fig. 1) near tunnel portals, road sections, in inhabited areas and locations of specific care, e.g. at schools. Unfortunately a detailed mapping of the concentration field along lines or arcs could not be fitted into the 4-month timeframe of the wind tunnel tests. Road segments were treated as line sources; the pollutants produced in the road tunnels were supposed to leave the road tunnel at the tunnel exit in traffic direction and modeled as point sources with a small horizontal momentum. Methane was used as tracer gas; samples were collected simultaneously by an automatic 24-channel sampling system and analyzed by a flame ionization detector afterwards (Fig. 5, right).

Figure 3: Vertical cross section view of the model arranged in the test section of the Göttingen-type wind tunnel
Repeatability tests gave an average relative error of 7.3%. Reynolds-number independency was ensured by the mean flow velocity of \( u_{\text{ref}} = 4.5 \text{m/s} \) at \( H = 50 \text{mm} \) height. In total 262 sets of concentration measurements, each consisting of 10 to 22 sampling points, were performed (background concentration and calibration gas were measured in each set). Each source was measured separately at each wind direction to determine the contribution of the different sources to the total concentration.

Full scale concentrations of \( \text{NO}_x, \text{PM}_{10} \) and \( \text{CO} \) were determined based on the normalized concentrations \( c^+ = c \cdot u_{\text{ref}} \cdot H^2 / Q \) from the modeling, the real traffic emissions of the individual sources and the background concentration. Among the pollutants mentioned, \( \text{NO}_x \) distributions will be analyzed in Section 5.
4 NUMERICAL SIMULATION

The wind tunnel tests were accompanied by numerical simulation of the same area using the MISKAM code, which was applied for flow and dispersion simulation over complex terrain for the first time.

The MISKAM code gained currency in environmental assessment practice due to the relatively simple model set-up and to the fast code able to run on a single processor PC. The model solves the RANS equation using a k-ε turbulence closure on a Cartesian grid of Arakawa-C type. Buildings are represented as blockouts from the grid. Dispersion of an inert pollutant is calculated by the advection-diffusion equation using the wind field simulation results. Vegetation effects can be accounted for by additional terms in the flow and turbulence equations. Details of MISKAM 5 are given by Eichhorn [15]. Extensive evaluation activities were undertaken by Eichhorn and Balczó [16] in the framework of COST Action 732.

For each junction grids of 1.5×1.5×2km with a resolution 6×15×4m were generated, and inflow and outflow zones of sufficient length were added, to prepare correct inflow conditions in the investigated area. Terrain height sunk to zero at the boundaries. Cell number of each grid was about 5 million. Simulation time on a 3GHz PC was about one week for a case.

![Figure 7: View of the MISKAM model domain of Junction 2](image)

5 RESULTS AND DISCUSSION

5.1 First results

Both wind tunnel and the numerical results showed that in case of road segments running on the surface, concentration limits are only exceeded in a narrow strip along the road, as opposed by more hundred meter long plumes caused by tunnel portals. The direction of the tunnel plumes is slightly modified by the topography as it can be seen in Fig. 8 at NE wind.

![Figure 8: Left: details of Junction 2 with sources and sampling points; right: surface concentrations of NOx [µg/m³] at NE wind direction in case of road variant v3 without ventilation stacks. Dots: wind tunnel measurement, contour plot: simulation](image)
On the top of hills speed-up, behind them separation zones could be observed (see e.g. Fig. 10). Pollution coming from viaducts has only very low influence on the surface concentrations.

5.2 Application of ventilation stacks

Upon our recommendation, the tunnel ventilation system design was extended by ventilation stacks which will exhaust polluted tunnel air in 20m height above ground and thus, avoid large concentrations at ground level. Such a solution was chosen in several longer road tunnels already realized (Fig. 9, right).

The stacks are located near the outlet portal, and based on the first results, at least 88% of the polluted tunnel air has to be exhausted through them to avoid limit exceedance near the portals (Fig. 9, left). The concept was checked in further numerical simulations. Vertical outflow velocity of the exhaust was set to 6 m/s. A detailed analysis of the flow and concentration field showed that the plume axis is in about 40m height above ground, and surface concentrations below the plume of stacks are significantly smaller than those at the tunnel portals (Fig. 10). However, stack West had to be heightened to 25m because of the steep topography. With original height the plume’s footprint on the surface would be too large (Fig. 11).

5.3 Comparison of wind tunnel and numerical results

The comparison of experimental and numerical results (Fig. 12) shows acceptable agreement in general. However, some deviations were observed, which are due to:
Figure 11: Surface concentrations of NO\textsubscript{x}, [µg/m\textsuperscript{3}] in Junction 2 at NE wind direction in case of road variant 3 with ventilation stacks in operation

- minor geometrical differences of wind tunnel and numerical model
- different source modeling
- different vegetation modeling (material of lower porosity was used in wind tunnel)
- known numerical model limitations: according [16], MISKAM predicts thinner and longer plumes than measured, and near-source concentrations are overestimated
- coarse numerical grid resolution.

Many of these errors are almost unavoidable in projects of such extent and deadline, but can be eliminated in a detailed validation measurement.

Statistic metrics after Chang and Hanna [17] were also applied, most of them can be categorized as good: normalized mean square error (NMSE) 3.35, fractional bias (FB) 0.313, geometric mean bias (MG) 1.16, and the fraction of predictions within a factor of two of the observed values (FAC2) 0.655 while some of them are only acceptable: geometric variance (VG) 3.31 and correlation coefficient 0.608. Considering these, simulation results were also accepted for the prediction of air quality.

Figure 12: Left: scatter plot; right: quantile-quantile plot of concentrations

6 CONCLUSIONS

The wind tunnel measurements and accompanying numerical simulations performed in this project showed that considering the year 2018, open road sections cause limit exceedance only along a narrow strip of some 50m while pollutant plumes from the tunnel portals can spread many 100 meters away.

The air quality study provided information on the necessary changes of the ventilation system. Effect of the proposed ventilation stacks on air quality was estimated.

Numerical simulation proved to be a reliable tool to understand and predict dispersion phenomena, but deviations from the experimental results signalize that – particularly in complex terrain – use of wind tunnel dispersion investigations providing data for evaluation and assessment of simulation results is still recommended.
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8 REFERENCES