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Final report of the CleverNet project

CLEVERNET - Deploying innovative sensor networks in cross-border regions

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Obsah

Executive summary

Internet of Things (IoT) sensor networks are a new technological phenomenon for increased efficiency and optimization of commercial enterprise operations. In the public sector, there is still no methodology on how to use these technologies for different agendas, no knowledge of their acquisition or operational costs, and no standards on how to publish the resulting data as open data to support the digital economy.

The CleverNet project focused on the use of IoT sensor network data for city transport and climate investment planning, as these two areas are strongly linked. While these agendas are often addressed separately by local governments, it is digitalisation that allows to measure the 'quality of place' assessed from many angles. Subsequent investments can then be well targeted and presented to the public in the form of evidence-based arguments.

This final report first presents the deployed sensor network and its composition, followed by key results from the transport and climate domains.

The next chapter is devoted to a more detailed analysis of the sites that were investigated primarily from a climate perspective and for which specific recommendations were proposed based on the data evaluated.

Appendix 1 provides the reader with an insight into the analysis of the heat island data, and the related Appendix 2 looks at the wind flow analysis of the sites. Annex 3 describes the specific output - the use of an algorithm to calculate the occurrence of frost and ice. Annex 4 assesses the conceptual approach to the acquisition of the sensor networks and also the technological capabilities of the LoRa network, i.e. it presents its advantages and limitations. The last and more extensive Annex 5, prepared by the University of Žilina, is an analysis of the application of the acquired traffic and climate data for different agendas of transport planning and modelling, transport safety, etc., which demonstrates the undoubted benefits of such data for different agendas and professions.

The CleverNet project has thus fulfilled its objectives, both the methodological grasp of sensor networks (for which it has also produced a separate manual) and the practical deployment of a sensor network in the form of an urban laboratory in a regional city. With the results presented, it demonstrates what practical benefits these technologies can have for local governments, but also for the state, in the field of digital spatial development planning, efficiency of management and asset management, security or citizen participation, digital education and literacy, as well as follow-up research and development activities. It has demonstrated the simplicity and speed of deploying sensor networks, where even in a rigid public administration environment, necessary and sufficient data can be obtained in a matter of months or units of years.

City traffic and climate lab in Žilina

Climate change has real impacts on the quality of life in Žilina. There are several places in the city centre that are at risk of heat island and the main causes are high traffic intensity and the associated large areas of transport infrastructure, lack of green space and some places struggle with the necessary ventilation.

The CleverNet project (Interreg SK_CZ programme, 2021-2022) has reached concrete results based on long-term traffic and climate monitoring using a unique Internet of Things (IoT) sensor network as an urban laboratory, which it deployed in the summer of 2021 and from which it is continuously extracting the necessary data. The subject of the evaluation is this year's data until 15 September 2022, when this article was written.

The aim of the CleverNet project is to present to the professional and non-professional public the benefits of sensory data applied in the practice of urban planning and development, transport planning and parking policy, climate change adaptation or traffic safety policy. The results thus affect all these agendas and are intended to serve as a guideline for the creation of an urban laboratory and subsequent work with data at the municipal level for better targeting of investments.

About the sensor network

The sensor network was designed to monitor the following phenomena:

- **The number of vehicles in the centre of Žilina:** traffic counts in the form of a virtual fence (geofencing) around the city centre, which is an example of a low-cost area-based transport policy solution made affordable for every municipality.

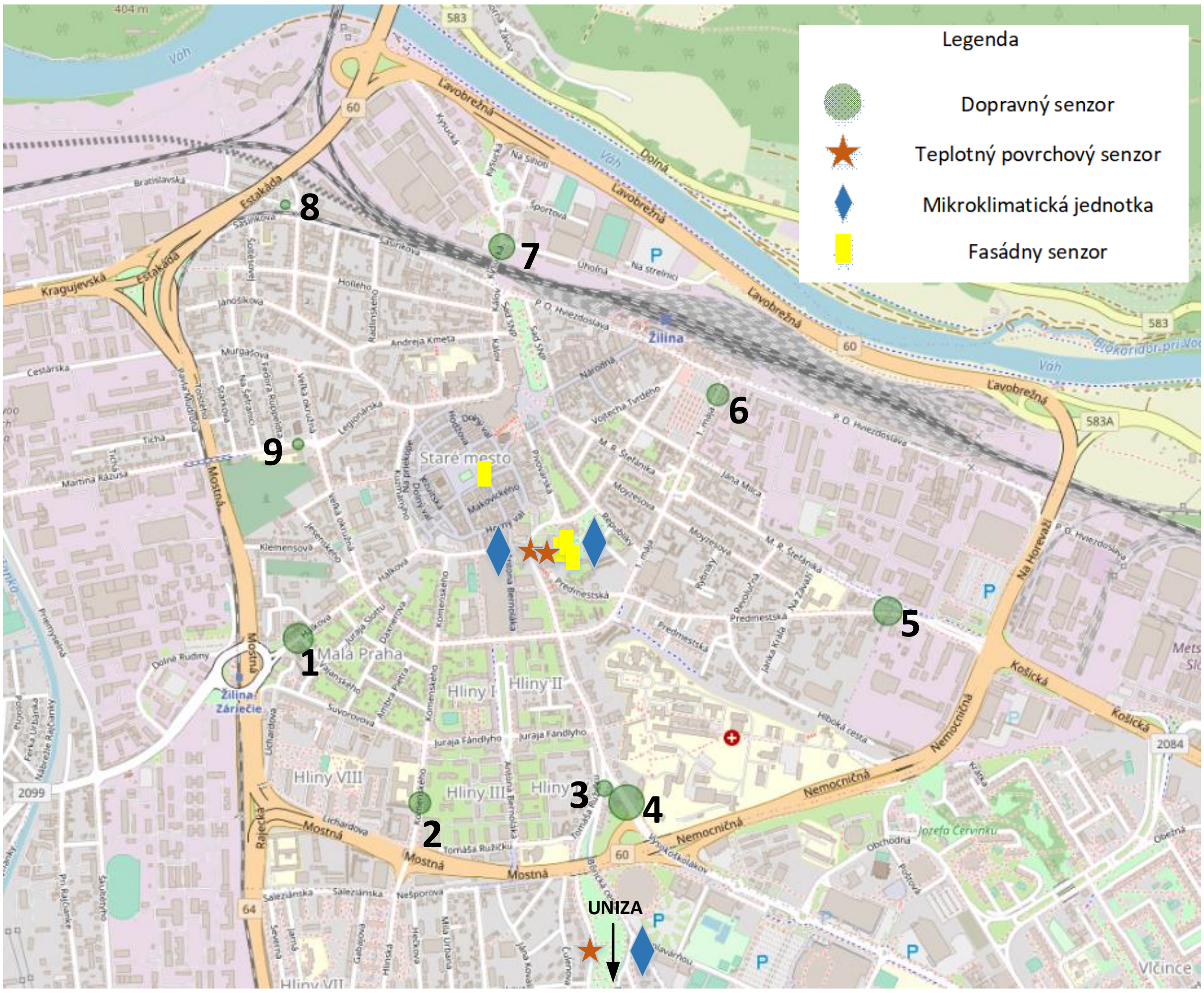
- **Safety at pedestrian crossings:** the use of traffic count sensors at pedestrian crossings, a total of 6 locations, and the creation of a traffic safety index providing a quick insight into speeding statistics as a tool for municipal police and traffic calming policies and other preventive measures at pedestrian crossings

- **Heat islands in the city centre:** weather stations, complemented by surface and subsurface temperature sensors at 6 cm and 30 cm depth, monitor the quality of the microclimate and the warming/cooling of the site. For the possibility of comparison, sites in the city centre have been typologically selected: a busy street with no significant greenery at the entrance to the Aupark shopping centre as a reference site where a heat island is expected, a nearby park Sad na Studničkách, where the microclimate of the park is monitored in the context of an overheated centre, and a third weather station located in the premises of the Žilina Science Centre, where the influence of the surrounding forest on the maximum temperatures and cooling of a similarly built-up area as the Aupark has been investigated.

- **Climate conditions for children:** a special temperature sensor at 80 cm above the ground to monitor the temperature that children aged 3-5 years old breath.

LoRa network | Traffic sensor | Microclimate unit | Frost sensor | Parking sensors | Façade sensor

Figure 1: Overview of deployed sensors



Legend: Traffic sensors, surface-and-under-surface temperature sensors, microclimate units, fasade temperature sensors

Figure 2: Location of sensors in the centre of Žilina

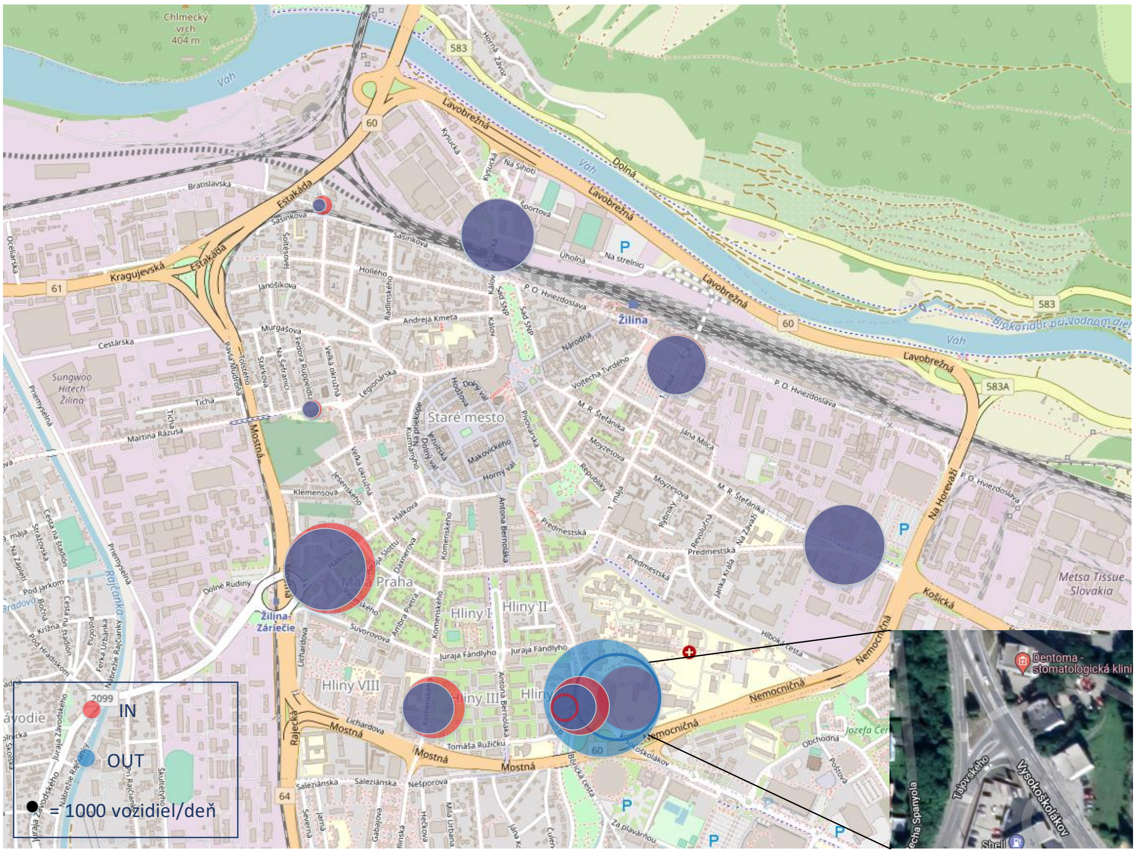


Figure 3: Traffic IoT geofencing (virtual fence) around the city centre

Figure 4: Weather stations and surface warming sensors deployed at sites in the city centre (Aupark (left) and Na Studničkách park on the right) and at the university site surrounded by forests (bottom right), data from 30th July 2022

Key results

Approximately 300 thousand vehicles enter the centre of Žilina every week. These vehicles need roads (13.5%) and together with buildings and their car parks they represent 44% of the total area of Žilina city centre. The green area accounts for a poor quarter of the area and one third of the area represents potential for new functions. The ratio thus suggests that to mitigate the impacts of climate change, there is a need to examine the functional use of areas without typical uses in favour of cooling the city and a greater proportion of green space in public areas, as well as to consider transport measures to reduce traffic volumes, a more consistent parking policy and shading of parking areas and streets. Given the good cooling capacity of the city, shading specific areas is the most efficient tool to eliminate peak periods that negatively affect the microclimate of the city.

Table 1: Areas in the centre of Žilina and their use

Type of area	m2	share of total area
Area without typical use (m2)-without buildings - TOTAL	**855 611**	**32,5 %**
Built-up area - including car parks	**798 047**	**30,5 %**
Road area - TOTAL	**356 750**	**13,5 %**
Usable green area (m2) - TOTAL	**568 812**	**21,5 %**
Cemetery (m2)	**33 510**	**1,5 %**
Orchard, garden - TOTAL	**5 270**	**0,2 %**
TOTAL AREA (m2)	**2 618 000**	**100 %**

Transport

On average, 43 930 vehicles enter the centre of Žilina daily, of which 6 120 are trucks. The full centre is accessed by 4,250 vehicles, of which 85 are trucks. The month with the highest traffic volume is May, with 1 474 759 vehicles, and the month with the lowest is February, with 1 173 257 vehicles.

The long-term evaluation (1-8/2022) shows that the southern direction (Komenský, Vysokoškolakov, Tajovského, 31%) and the northern direction (Kysucká, 1. Mája, Bratislavská, 31%) are the most congested, followed by the western direction (Hálkova, Rázusa, 22%) and the eastern direction (Košická, 16%).

Conclusions:

In terms of future parking policy, it is suggested to focus attention on the area of the railway and bus station, where the climatic conditions are the worst of the areas in the city centre, see below. Parking in P+R (or rather P+B) car parks, with zoning regulations, will reduce traffic volumes and provide space for greenery and new housing at the expense of road space. It seems appropriate to build these capacities at the feeder roads to the "motorway" network, i.e. Kysucká, Hálkova, Vysokoškolakov and Košická according to the parameters of zonal regulation. The daily intensities and their course suggest that the capacity should be 800 to 1500 parking spaces in total.

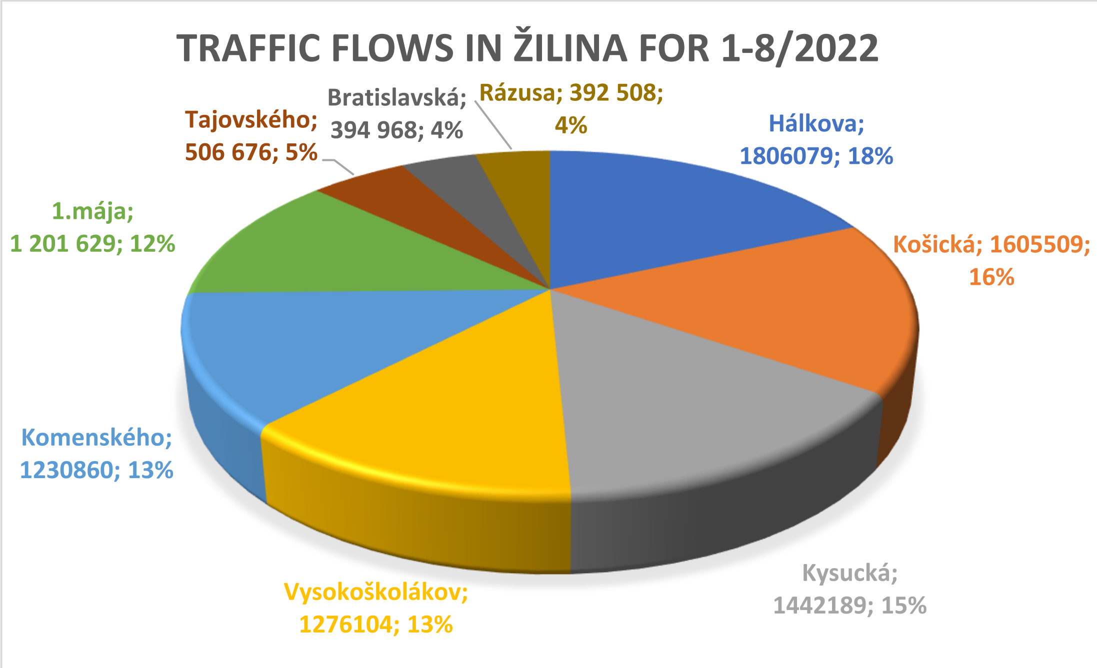


Figure 5: Traffic volume composition in the centre of Žilina, January to August 2022

Regarding traffic safety at the 6 monitored pedestrian crossings, it was found that about 20% of vehicles exceed 60 km/h, especially at night when traffic volumes are low. The worst crossing is sovereignly Hálkova (up to 60%), followed by Komenského (52%) and Vysokoškolakov (42%), while the safest crossing is Tajovského, where vehicles naturally slow down due to the crossing.

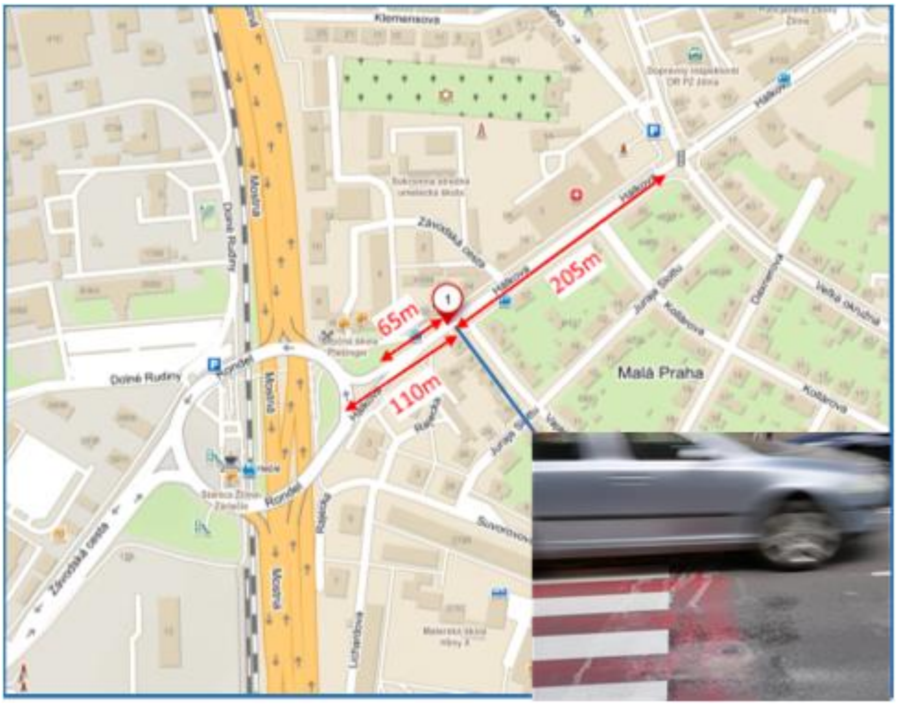


Figure 6: Traffic safety monitoring on Hálkova Street

City climate

Žilina cools very well due to its location and altitude, but the heat island problem occurs in several places in the centre that require investment in the quality of public space. While the number of cold days (below 0 °C) is the same for all three locations; the number of tropical days (above 30 °C) varies significantly and points to places that are affected by climate change and represent a higher burden on public health.

The metric of the number of tropical days was applied to all three sites, also at an hourly resolution. The Aupark site in the city centre had 28 of these days, 4 more than the similar built environment at the university, and the effect of the forest around the university also influenced the average temperature, which is almost one degree lower. A much greater difference was then recorded by the city park Sad na Studničkách, which is approximately 200 m away from the Aupark site. Although the distance is relatively small, the park recorded only 13 tropical days, less than half as many as Aupark, a 40% difference in hours, and the average temperature was only 0.6 °C lower. This suggests that the park environment is also strongly influenced by the built environment of the surrounding centre and the average temperatures here are even higher than in the built environment of the university.

It is also interesting to compare the maximum temperatures among the sites; on 30 June the highest values were recorded, namely Aupark 38 °C, Sad na Studničkách 34.8 °C and the University 36.2 °C, i.e. the compact green area of Sad na Studničkách was only able to provide a cooler microclimate by 3.2 °C, which suggests that this green island in the city centre is very isolated and Žilina needs at least two other similar sites, connected by green corridors to have a significant green effect on cooling the city centre. On the other hand, the temperature at the University shows that the surrounding forest park is able to cool the built-up area of the University by 1.8 °C.

Impact on children

The situation for young children is much more serious. The heat breathed by adults is much lower than for children. At the Aupark site, we found that for children the environment was in tropical day mode for 90 days, more than triple the 28 days for adults, and triple in number of hours. The average temperature was 1.3°C higher, but the maximum temperatures were much more severe: while the maximum at adult height was 38°C, the maximum at young children's height was 44.1°C, an increase of more than 6 degrees, which is alarming considering the natural body temperature. A child who is overheated in this way is thus exposed to dehydration on the one hand, but also to a higher risk of exposure to fumes and dust particles from traffic on the other. In addition, the subsequent cooling in the shopping centre is very likely to cause respiratory problems and summer colds. Aupark can thus be classified as a location with an increased health burden and risk of asthma.

The built-up areas of Aupark or the university have a much higher number of tropical days at 80 cm height. In both cases, temperatures above 30 °C are three times more frequent at this height and can be used as a parameter for similar built-up areas in the city, including transport infrastructure. The site thus requires an intervention in the public space in favour of green space, at least in the form of parklets, and against traffic.

Climate conditions of Žilina city centre in 2022 in a summary table

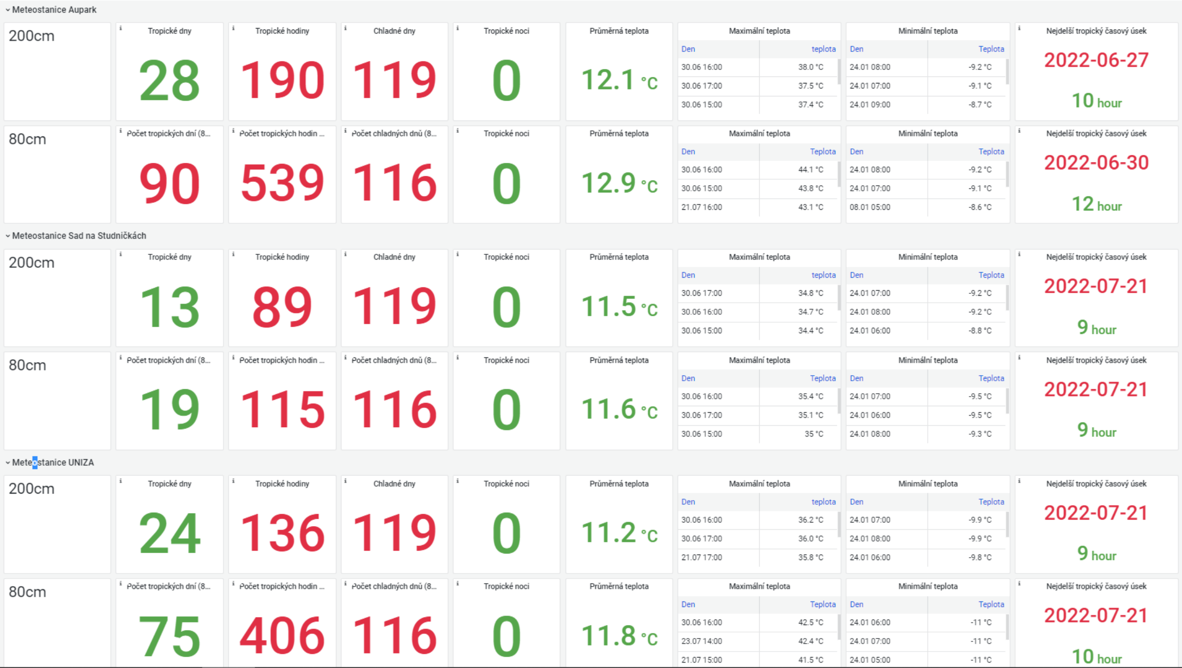


Figure 7: Overview of the basic climatic parameters of the city of Žilina for the year 2022

Data available at: https://doprava.digital/d/XTTn-hM4k/dlouhodoby-prehled?orgId=1&from=now/y&to=now/y&var-company_id=10&var-group_id=2&var-meteo_ids=All&var-frost_ids=All

Heating and cooling of surfaces

Surface heating has a significant impact on the microclimate of a site and its ability to cool. Two temperature sensors have been deployed at the Aupark site: a traffic sensor with temperature measurement, located at the pedestrian crossing in the asphalt roadway between Aupark and the new City Hall, and a standard subsurface temperature sensor located in the pavement at the entrance to the new City Hall. The temperature at 30 cm below the ground reached a maximum on 22 July (32.5 °C), the temperature at 6 cm below the ground reached a maximum during the first heat wave (30th June, 44.8 °C) and the maximum surface temperature then reached 51.3 °C.

While it was still relatively cool on 12th July and the daytime heat was eliminated by the cool night (only 11 °C on the morning of 13th July), on 25th July the tropical daytime temperatures already had a significant effect on surface warming (ca. 24 °C) and the accumulated energy remained high for the next few days, affecting the ability to cool surfaces. The following table illustrates that a heat island is created by consecutively heating surfaces, which transfer their thermal energy to lower layers that are more thermally stable and cool over the long term, and which return energy back to the surfaces at night, reducing the night-time cooling effect.

The concrete pavement/asphalt cooled on average by 24 °C/ respectively 15 °C; on 25th July it was 2 degrees more (26 °C/17 °C), but this energy was stored in the ground, as evidenced by the temperatures in 30 cm, where despite a significant cooling (on 1st August the morning temperature was 13.3 °C) the temperature in 30 cm only dropped to 20.4 °C and rose again after the warming, e.g. on 31st August the morning temperature was 12.7 °C and in 30 cm it was 25.4 °C). The temperature in

30 cm only fell below 20 °C in mid-September (on 13th September the morning temperature was 8.5 °C and in 30 cm 19.1 °C).

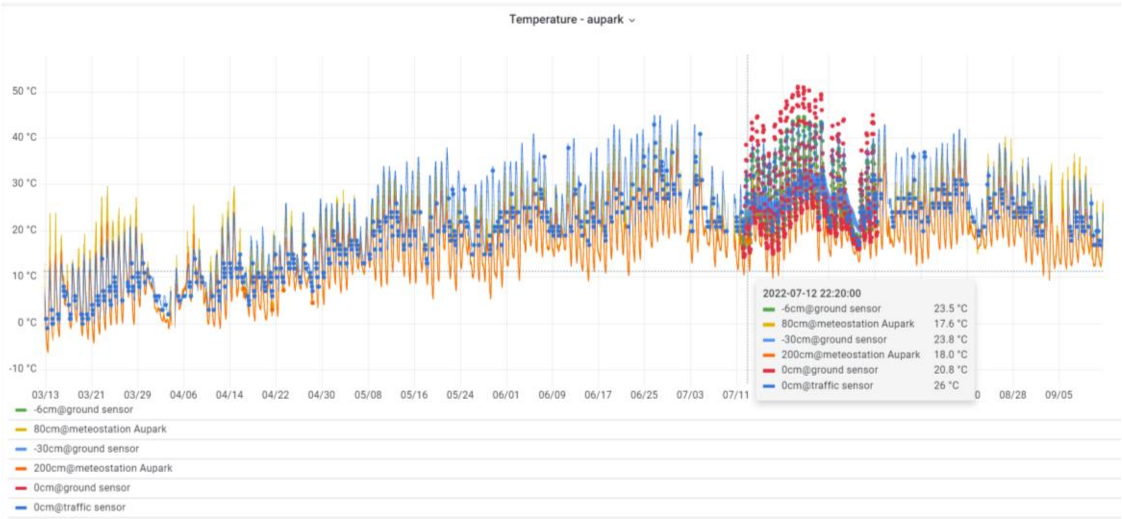


Figure 8: Summary of temperature data in the centre of Žilina at six height levels

Aupark cooling

Table 2: Temperatures comparison and potential for cooling Aupark location – temperatures in °C

	12th July 2022			**25th July 2022**			**29th July 2022**		
Temperature in the height of in cm	afternoon peak at 15:30	evening drop at 22:20	13.7. morning saddle at 6:35	afternoon peak at 15:30	evening drop at 22:20	26.7. morning saddle at 6:35	afternoon peak at 14:15	evening drop at 22:20	30.7. morning saddle at 6:35
200	23,7	18	10,8	32,9	24,9	17,4	29,9	19,2	17,8
80	28	17,6	11,3	38	24,1	18	33,7	19,6	18,2
0 concrete pavement	38,6	20,8	14,6	**49,6**	29,3	**23,7**	44,1	**22,6**	**20,7**
0 asphalt	32	26	17	**43**	34	**26**	37	**26**	**22**
-6	31,2	23,5	16,6	43	32,8	25,8	36,4	24,5	21,8
-30	21,6	21,6	21,6	29,2	**31,9**	**30,1**	26,8	27,7	25,9

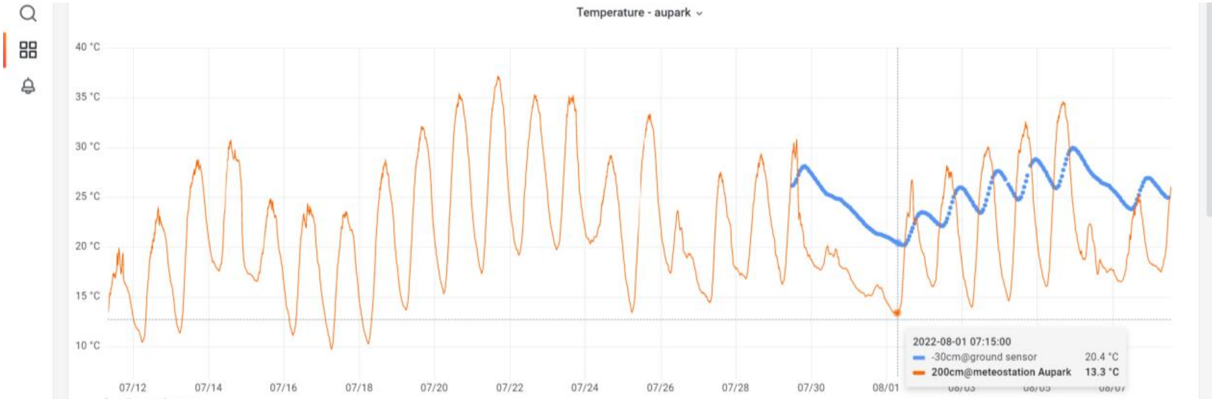


Figure 9: Detail of the comparison of air temperature changes at 2 m height and temperatures 30 cm below the surface

While temperatures below 25°C have relatively little effect on heat accumulation to street surfaces, a series of very warm days can eliminate the strong potential of the city's altitude and location. Žilina has no tropical nights in 2022 and can cool down very effectively in relatively warm weather unless it is a multi-day heatwave series. The temperature at 30 cm below the ground remains absolutely stable and the other layers cool down according to the phases of the day. The pavement can get much hotter than the asphalt because the sensor is placed in a relative windless environment, whereas the sensor in the asphalt is driven over by vehicles and the road here is also a wind corridor. However, the asphalt clearly shows that in terms of energy accumulation, it is a heat island supporting surface (e.g. on 25.7 the pavement cooled by 26 °C while the asphalt only cooled by 17 °C).

Locations affected by heat islands

The deployed sensor network is still insufficient for some purposes. Thus, additional data was used to identify heat island affected locations:

- **Data from satellite imagery** (source World from Space), informative identification of heat islands - preparation of measurement specifications.
- **Data from daily measurements using a portable temperature sensor at 200 cm**, comparison of temperatures with the reference Aupark site, made on 31st August 2022.
- **Data from nighttime measurements using portable temperature sensor at 200 cm**, comparison of temperatures with Aupark reference site for cooling potential, performed 7th September 2022

Results of daytime measurements: apart from traffic areas (intersections), locations with heat island (red) and locations affected by heat island (yellow) are colour coded. As each site was measured at different times, the temperature difference with respect to Aupark at 200 cm was used as a key parameter. In total, 13 sites were thus identified as requiring the application of climate change mitigation measures.

Impact of the urban park Sad na Studničkách on the cooling of the city centre

The frequency of wind speeds on the Aupark vs. Sad wind direction beautifully illustrates (yellow contours on the left (N) and on the right on the SW) how the municipal building located between these sites impedes the flow towards the centre. Thus, the park's effect on cooling the centre is very small and this effect needs to be supported by additional green spaces connected by green corridors.

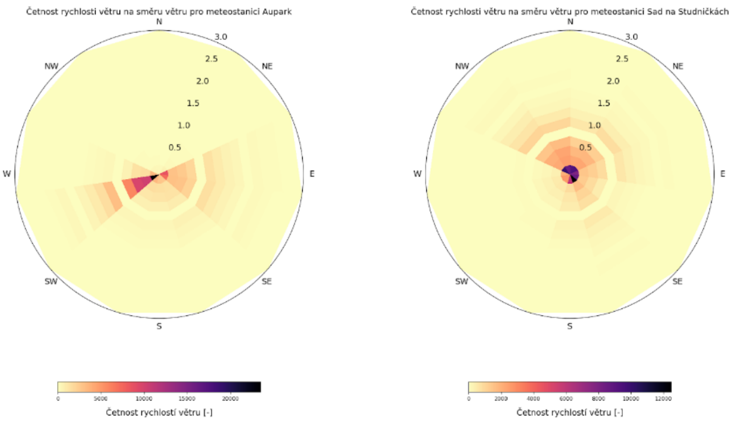


Figure 10: Example of measurement results from two weather stations with wind sensors, identifying the city office building as an obstacle to wind flow and therefore eliminating the effect of the park on cooling the city centre

The stable long-term data from the weather stations provide a reference for the investigation of other sites, which was carried out using a portable temperature sensor on 31st August during daytime hours and 7 September at night. It was thus possible to take manual measurements and compare the sites with each other, thus analysing dozens of sites in the city centre and identifying heat islands. These are marked in the following table in red (critical sites) and yellow (potentially critical sites)

Table 3: Results of daily measurements (31st August) – identification of heat islands

Street name	Measured temp °C	0,8m Aupark	0,8m Sad	2m Aupark	2m Sad	diff 0,8m Aupark	diff 0,8m Sad	diff 2m Aupark	diff 2m Sad
Velká Okružná + Komenského	28,777	30,871	22,393	22,521	21,397	-2,094	6,384	6,256	7,38
Velká Okružná + Vojtecha Spanyola	27,97	30,229	22,365	22,082	21,195	-2,259	5,605	5,888	6,775
P, O, Hviezdoslava (Autobusové Nádraží)	25,677	24,953	21,216	20,359	19,383	0,724	4,461	5,318	6,294
Velká Okružná + Hálkova	27,612	30,76	22,891	22,729	21,607	-3,148	4,721	4,883	6,005
J,M, Geromettu (Tržiště)	26,425	28,043	22,645	22,502	21,438	-1,618	3,78	3,923	4,987
Jozefa Vuruma (Center)	26,038	28,893	22,35	22,232	21,244	-2,855	3,688	3,806	4,794
Sad SNP	25,572	25,043	22,146	21,921	21,059	0,529	3,426	3,651	4,513
Sad SNP + Fárské schody	25,105	25,184	22,12	21,611	20,587	-0,079	2,985	3,494	4,518
P, O, Hviezdoslava (Nádraží)	23,997	25,105	21,428	20,748	19,664	-1,108	2,569	3,249	4,333
Vojtecha Tvrdého + M,R Štefánika	23,7	23,223	21,311	21,084	20,192	0,477	2,389	2,616	3,508
Vojtecha Tvrdého	23,728	23,673	21,199	21,328	20,416	0,055	2,529	2,4	3,312
Fárské schody	24,63	25,613	22,693	22,299	21,359	-0,983	1,937	2,331	3,271

Štúrova + Horný Val	24,986	25,665	22,113	22,698	21,54	-0,679	2,873	2,288	3,446
Dolní Val (South)	23,85	24,869	21,385	21,871	21,139	-1,019	2,465	1,979	2,711
Národná	22,992	25,43	21,611	21,239	20,37	-2,438	1,381	1,753	2,622
Na priekope (Center)	23,203	23,048	21,095	21,767	21,073	0,155	2,108	1,436	2,13
Makovického	23,98	24,922	21,959	22,661	21,539	-0,942	2,021	1,319	2,441
Farská ulička + Dolný Val	23,654	24,989	22,453	22,355	21,478	-1,335	1,201	1,299	2,176
Antona Bernoláka (North)	23,523	24,263	21,771	22,276	21,365	-0,74	1,752	1,247	2,158
Dolní Val + Sladkovičova	23,907	24,795	22,404	22,695	21,807	-0,888	1,503	1,212	2,1
Mydlárska	23,948	26,904	23,086	22,74	21,789	-2,956	0,862	1,208	2,159
Sladkovičova + Na priekope	23,87	25,722	22,405	22,692	21,748	-1,852	1,465	1,178	2,122
Na priekope (North)	23,697	24,615	22,227	22,727	21,75	-0,918	1,47	0,97	1,947
Pernikárska + Horný Val (Parking place)	23,267	24,002	21,539	22,301	21,409	-0,735	1,728	0,966	1,858
Jezuitská	22,698	23,316	21,475	21,807	21,123	-0,618	1,223	0,891	1,575
Mariánske námestie	22,878	22,163	21,169	22,031	21,317	0,715	1,709	0,847	1,561
Bottova	23,427	23,672	21,578	22,581	21,479	-0,245	1,849	0,846	1,948
Aquapark	23,11	24,027	21,844	22,301	21,403	-0,917	1,266	0,809	1,707
Antona Bernoláka (South)	23,107	24,133	21,641	22,318	21,372	-1,026	1,466	0,789	1,735
Jezuitská + Dolní Val + Jána Kalinčiaka	22,545	22,338	20,923	21,781	21,125	0,207	1,622	0,764	1,42
Hodžova (North)	23,435	23,646	22,039	22,682	21,693	-0,211	1,396	0,753	1,742
Farská ulička	23,205	30,352	22,832	22,458	21,57	-7,147	0,373	0,747	1,635
Horný Val	23,127	23,412	21,594	22,441	21,447	-0,285	1,533	0,686	1,68
Na bráne	22,757	23,977	21,635	22,305	21,383	-1,22	1,122	0,452	1,374
Dolní Val (North-East)	22,812	23,383	21,516	22,469	21,594	-0,571	1,296	0,343	1,218
Jána Kalinčiaka	22,177	22,385	20,997	21,849	21,195	-0,208	1,18	0,328	0,982
Radničná	22,225	22,445	21,283	22,203	21,383	-0,22	0,942	0,022	0,842

Table 4: Results of night-time measurements (7.9.) – identification of heat islands – site cooling rate

Street name	Measured temp °C	0,8m Aupark	0,8m Sad	2m Aupark	2m Sad	diff 0,8m Aupark	diff 0,8m Sad	diff 2m Aupark	diff 2m Sad
Vojtecha Tvrdého + Daniela Dlabača (před parkovištěm)	18,39	17,656	16,439	17,771	17,131	0,734	1,951	0,619	1,259
Velká Okružná + Hálkova (Křižovatka)	16,705	16,23	15,438	16,48	15,949	0,475	1,267	0,225	0,756
Národná	17,77	17,352	16,371	17,586	17,037	0,418	1,399	0,184	0,733
Velká Okružná + Vojtecha Spanyola (Křižovatka)	16,853	16,566	15,518	16,723	16,078	0,287	1,335	0,13	0,775
Velká Okružná + Komenského (Křižovatka)	16,755	16,542	15,474	16,604	16,003	0,213	1,281	0,151	0,752
Namestie Andreja Hlinku	17,267	17,055	16,307	17,409	16,974	0,212	0,96	-0,142	0,293
J.M. Gerometttu (Tržiště)	17,31	17,113	15,787	16,924	16,406	0,197	1,523	0,386	0,904
Mariánske námestie	17,207	17,013	15,831	16,922	16,357	0,194	1,376	0,285	0,85
Jezuitská + Dolní Val + Jána Kalinčiaka	16,98	16,809	15,895	16,963	16,576	0,171	1,085	0,017	0,404
Dolní Val (parking place)	17,02	16,881	16,049	17,066	16,699	0,139	0,971	-0,046	0,321
Pernikárska (parking place)	17,22	17,089	15,719	16,905	16,228	0,131	1,501	0,315	0,992
Jezuitská	17,003	16,883	15,854	16,924	16,535	0,12	1,149	0,079	0,468
Antona Bernoláka (South)	16,997	16,885	15,619	16,834	16,162	0,112	1,378	0,163	0,835

Site analysis and proposals for solutions

To propose specific measures, the city centre was divided into logical units/areas according to the climatic conditions. Each area was analysed separately, and recommendations were made for both the long-term measurement of climatic or other conditions and for their revitalisation with regard to the impacts of climate change.

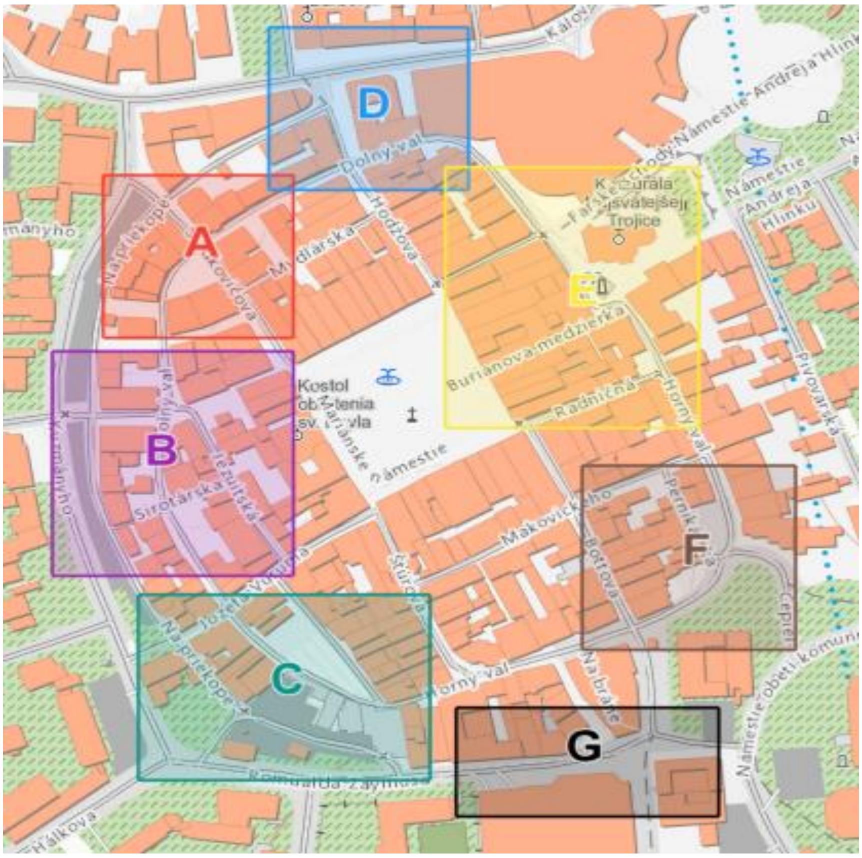


Figure 11: Division of the subject areas of the centre into locations A to G for more detailed examination

The town centre is largely built up with buildings. The streets between them are generally paved; asphalt covers are found on the south side of town. There is a very small amount of vegetation in the centre, apart from the centre of the city centre, an area of green space in the northern part (Na Prikope), the area around the car park (Horný val) and the western part of the centre. The vegetation belt in Na Prikope Street acts as a shield, however, due to the high density of buildings, the effect of vegetation on the centre is minimal. The following overview table has been compiled to compare the sites and to identify the critical areas that require intervention in terms of climate change (marked in red):

Table 5: Parameters monitored and their role in the assessment of risk sites in Žilina city centre with regard to climate change impacts in relation to traffic

	Wind flow	vegetation shield	shadowing	Density/height of buildings	parking lot	traffic and pollutants
Location A	closed	reduced	good		yes	
Location B	open		good	high		
Location C	open				yes	yes
Location D	open	good from the North only			yes	
Location E	open	weak	bad	high		
Location F	open	optimal			yes	
Location G	open	none	bad		yes	yes

Conclusions:

Based on the data from the deployed traffic-climate sensor network and the survey conducted, we have reached conclusions that point to problem areas where traffic significantly affects climate. Area C - Marketplace and Area G - Aupark were found to be the most serious candidates for traffic and parking regulation along with climate change measures. The highest risk areas were identified in the northeast of the city close to the main train station. Other areas of risk are in the area around Velká okružná, particularly at junctions that serve to carry wind flow around the city. The southern part of the centre is sufficiently covered by vegetation.

Location in the city centre

Location A - North side of Na prikope and Sládkovičova

The western vegetation shield on Na Prikope Street is greatly reduced in Area A. The centre of Area A (Dolný val and Sládkovičova) is closed to wind flow, there is also a large car park in the area, which is covered by a high-rise building facing south, for this reason the area is well shielded from solar radiation.

Recommendation: stretch the vegetation shield of Na Prikope and possibly reconstruct the parking lot. The last option is to improve Sládkovičova Street, more precisely its southern part in front of the entrance to Mariánské náměstí.

The wind flow is blocked by buildings from all directions.

Location B - Jána Kalinčiaka

Area B is characterised by a high density of buildings. The advantage of this area is the open corridor of air flow from the West and partly from the East. The orientation of the street is west-easterly and sunlight is blocked from the East.

Recommendation: the area is suitable for wind and temperature measurements similar to the Aupark site.

Location C - Market Place

The Marketplace is an open area from the South, recently redeveloped. The southern buildings have been demolished, increasing the wind flow from the South, and have been replaced with concrete (parking lots, etc.), increasing the risk of high daytime temperatures. Air quality is thus at risk in the Market Place area due to the open-air flow from the South, passing through the Komenský-Velká okružná and Hálkova-Velká okružná intersections. Approximately 10 000 cars per day pass through these junctions. The pollutants from this road subsequently reach the Market Place area when the wind is from the South to the North (in 26% and the South directions account for up to 50% of the total flow).

Recommendation: the area is suitable for wind and temperature measurements similar to the Aupark site with the addition of particulate matter and NOx measurements.

Recommendation 2: Deploy taller vegetation from the South of the Marketplace to provide shade to the Marketplace area. The vegetation will subsequently block pollutants from the South Road.

- The area of the Market Place area is 7623 m2, the tarmac area represents approximately 50% of the Market Place area.
- The green area from the South 400 m2 represents 5% of the area
- The green area from the West 1105 m2 represents 14 % of the area
- Parking area 2874 m2 represents 37 % of the area
- Market area 1401 m2 represents 18% of the area
- Building area 1981 m2 represents 26 % of the area
- NDVI (normalised difference vegetation index)
    - 94 % ... 0
    - 3 % ... <0,3
    - 3 % ... >0,3

Location D - Hodžova

Area D is open to airflow from the north and partly from the south. The area has an increased presence of vegetation from the north, so the influence of vegetation only applies if the wind is coming from the north. The south side is influenced by temperatures from the centre.

Recommendation: the area is suitable for wind and temperature measurements similar to the Aupark site.

Recommendation 2: Vegetation treatment would be appropriate for Hodžova Street, specifically the parking lot.

Location E - Cathedral and Andrej Hlinka Square

Area E contains the tallest buildings, i.e. specifically the tower, the cathedral and part of the department store. Farská (Parish) Street has the highest ratio of width between buildings to height, is oriented west and is open to the airflow from the East and partially open from the West. Sunlight is accessed from the East, with the western part partially blocked by a building that subsequently shades the sunlight in the afternoon.

The area of Andrej Hlinka Square has enough vegetation in the northern part of the square, however, the amount of vegetation in front of the entrance to the Parish Steps (Farské schody) is drastically reduced. Moreover, the area is not shaded in any way.

- The area of the Farská ulička area is 200 m2
- The length of the alley is 61 m and the width of the alley is 3.3 m
- The floor of the alley is made up of stone paving only
- Average height of surrounding buildings is 15,5 m

Recommendation: the area is suitable for wind and temperature measurements similar to the Aupark site.

Recommendation 2: Add more greenery around the cathedral and tower.

Recommendation 3: Add more greenery in the area on the south side of Andrej Hlinka Square (area in front of the department store and Farské schody).

Location F - Pernikárska Street

Area F has optimal vegetation conditions throughout the city centre. The southern part contains elevated vegetation. The parking lot is blocked by trees that face south and cast shade on the parking lot.

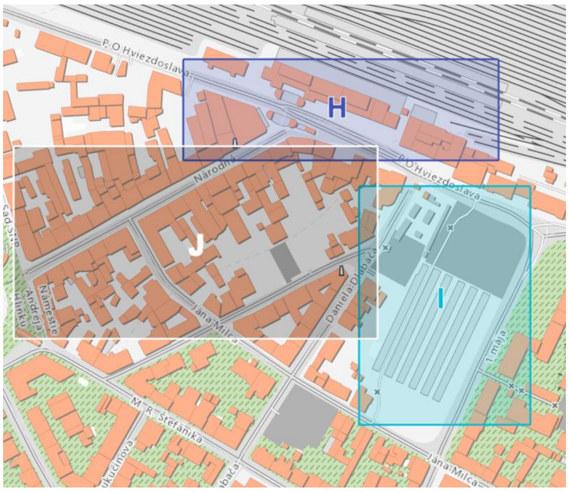
Recommendation: the area is suitable for wind and temperature measurements similar to the Aupark site. Due to the increased vegetation and open space, it is recommended that surface temperature sensors should be installed to measure surface temperatures in the parking lot and adjacent roadway. This is due to the increased risk of icing in winter.

Location G - Aupark

Location G is metered. There is an increased density of population movement in the location due to the entrance to Aupark. The area faces west-east and is open to wind flow from both sides. Sunlight is not blocked in any direction.

Recommendation: increase the amount of vegetation in front of the entrance to the mall, prevent vehicles from entering, i.e. expand the residence zone in front of the mall.

Location outside the centre



Location H - Train Station

The station faces west-east, as does the road, so the wind flow is fully open on both sides. In any case, the wind flow is reduced by the dense development located opposite the entrance to Národná Street and in front of the entrance to the railway station. Approximately 10 000 cars pass along the P.O. Hviezdoslava road during the day. Due to the lack of wind flow, pollutants remain near the train station. These pollutants consequently increase health risks and cause an increase in the heat island effect. Furthermore, due to the increased intensity of population movements and traffic in front of the station, air quality measurements are recommended.

Recommendation: The area is suitable for wind and temperature measurements similar to the Aupark site with the addition of particulate matter and NOx measurements.

Recommendation 2: Revitalize the area so that objects that block wind flow are replaced with taller vegetation to reduce ambient temperatures and absorb pollutants from traffic.

Location I - Bus Station

The bus station is a large open asphalt area that causes high temperatures during the day. The area is closed to the wind flow from all directions, preventing natural cooling. The bus station is surrounded by low vegetation (grassland only) with an irregular presence of trees. There is no greenery in the inner part. The area has raised roofs that cover part of the area and create shade.

Recommendation: The area is suitable for wind and temperature measurements similar to the Aupark site.

Recommendation 2: Vegetation treatments; increase the percentage of green space at the bus station, double the amount of trees and add shrubbery around the bus station. The increased tree intensity should be on the south side. Because of the closed structure to airflow from the South, adding more trees to the South side should not be a problem. The canopy over the bus stops could be repainted with a reflective material to increase the reflectivity of the incident light.

Recommendation 3: It is recommended that trees be planted at the adjacent parking lot on Daniela Dlabača Street to create shade in the afternoon.

Location J - Vojtecha Tvrdého and Národná streets

The most at-risk street in Area J is Vojtecha Tvrdého Street. The street is facing southwest. Wind flow is blocked from both sides. There are two parking lots in the area that are very close to each other. The parking lot by the bus station is asphalt, the other is paved with concrete blocks.

Národná Street is the most congested street in the city regarding population movement. Along the street, trees are planted in one row to reduce the temperature effect. The problem of this street occurs in the northern part, which is connected to the train station. More on the solution to this problem is described in Area H - Train Station.

Recommendation: reduce the number of parking spaces in the parking lot and replace them with green space that would create shade for the parking lot.

Location K - Intersections between Velká okružná - Hálkova and Velká okružná - Komenského

Due to the large vehicle movements, approximately 10,000 per day, the area is suitable for monitoring wind speed and direction for air quality reasons. The intersections are fully open in all directions. The debris generated at the intersections affects the population depending on the wind direction.

Recommendation: The worst intersection in terms of temperature fluctuations is Velká okružná - Hálkova, which is recommended for measuring air temperature.

- The distance to the centre from the Velká okružná - Hálkova intersection is 230 m
- The area of the area Velká okružná - Hálkova is 5 556 m2
- The green area of the Velká okružná - Hálkova area of 1 719 m2 represents 30% of the area
- The area of buildings in the Velká okružná - Hálkova area of 1 348 m2 represents 24 % of the area

Using data from [1], the intersection was identified by respondents as a location with extreme temperatures and poor air quality.

- The distance to the centre from the Velká okružná - Komenského intersection is 270 m
- The area of the Velká okružná - Komenského area is 4 542 m2
- The green area of the Velká okružná - Komenského area of 663 m2 represents 14 % of the area
- The area of buildings in the Velká okružná - Komenského area is 1 562 m2 representing 34 % of the area

Using data from [1], the intersection was identified by respondents as a location with extreme temperatures.

Recommendation 2: Plant trees at this intersection in the area next to the parking lot on the south side.

Climate Conclusions

Žilina is a city that cools very well due to its location and altitude, as evidenced by the fact that there was not a single tropical night in Žilina in 2022, although there were 28 tropical days. A significant part of these places is related to traffic, so the key places to address are:

Aupark site - requires greenery that does not obstruct air flow, requires reconstruction of the public space in front of Aupark accompanied by a change in traffic regulation and a stricter parking policy in the area.

Bus station site - requires significant reconstruction

The problem is the hot afternoons in summer, which accumulate energy that is radiated into the surroundings even after 11pm, and which plagues visitors to the city centre, especially young children.

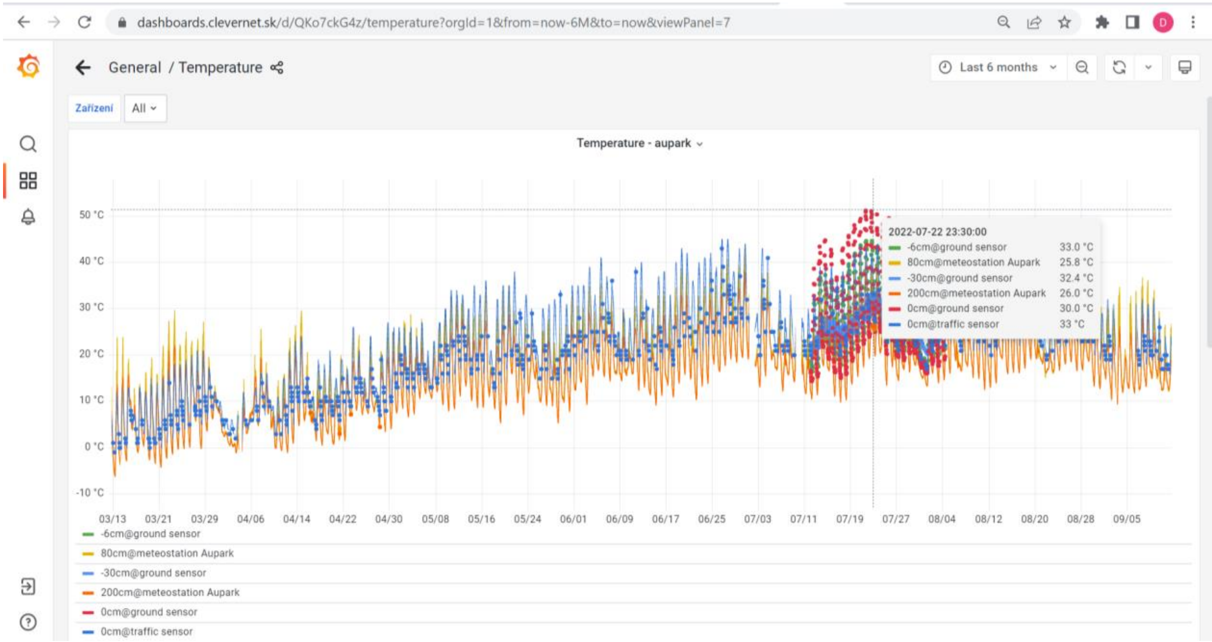


Figure 12: Data-based temperature differences at the Aupark site requiring the application of climate change mitigation measures

Annex 1: More detailed assessment of heat islands: background to the report

The analytical work was based on measurements/data from the sensor network according to the global criteria for heat island identification.

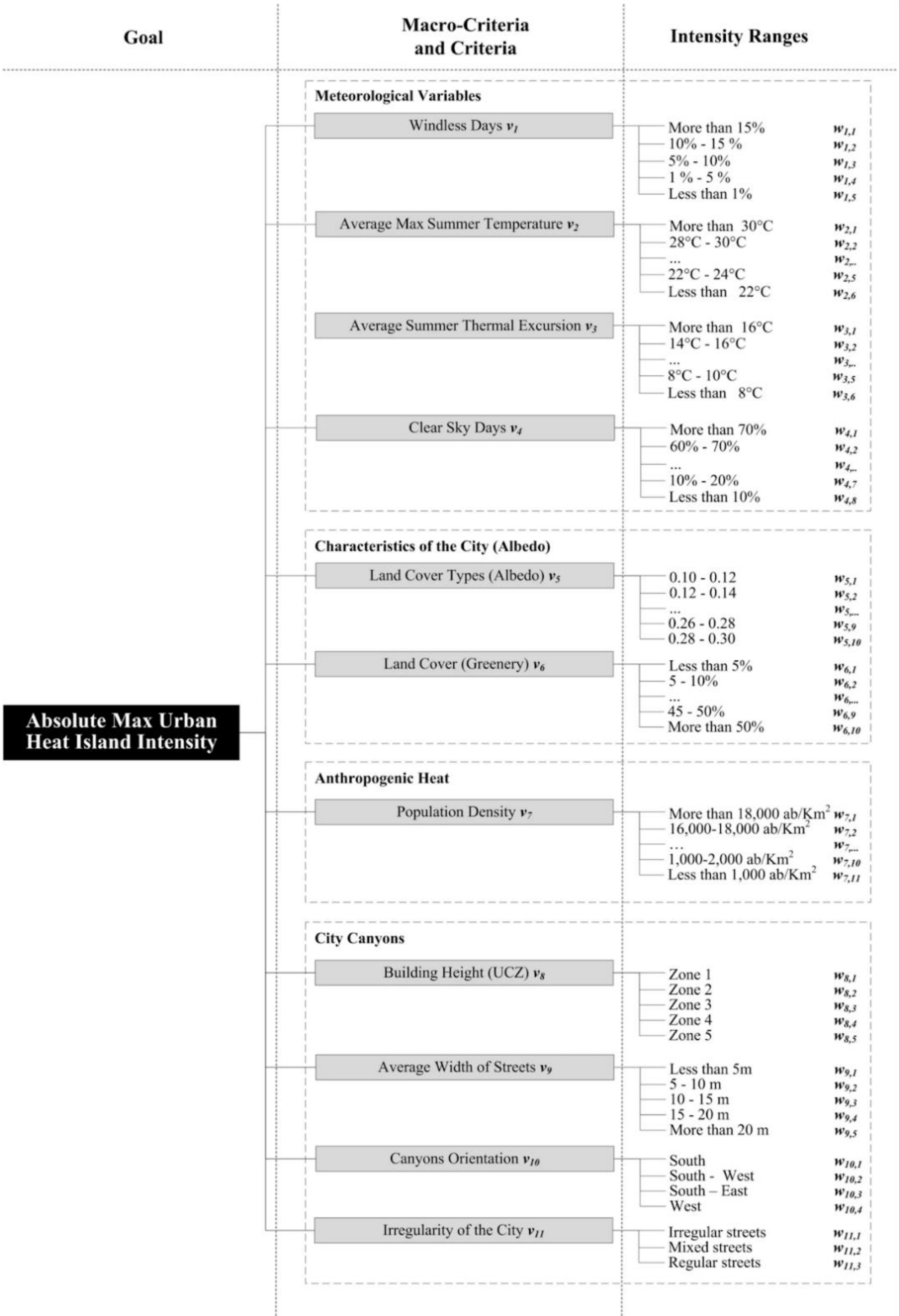


Figure 13: Heat Islands - Basic Evaluation Criteria and Range of Values [2]

Selected locations Žilina

Existing data sources (satellite climate data http://zelenza.worldfrom.space/ and statistics of the affected population https://www.zilina.sk/zivot-v-meste/o-meste/statistika-o-pocte-obyvatelov-2021/) were used to design the study sites. A total of 29 locations were selected and optimal routes for the measurements were proposed:

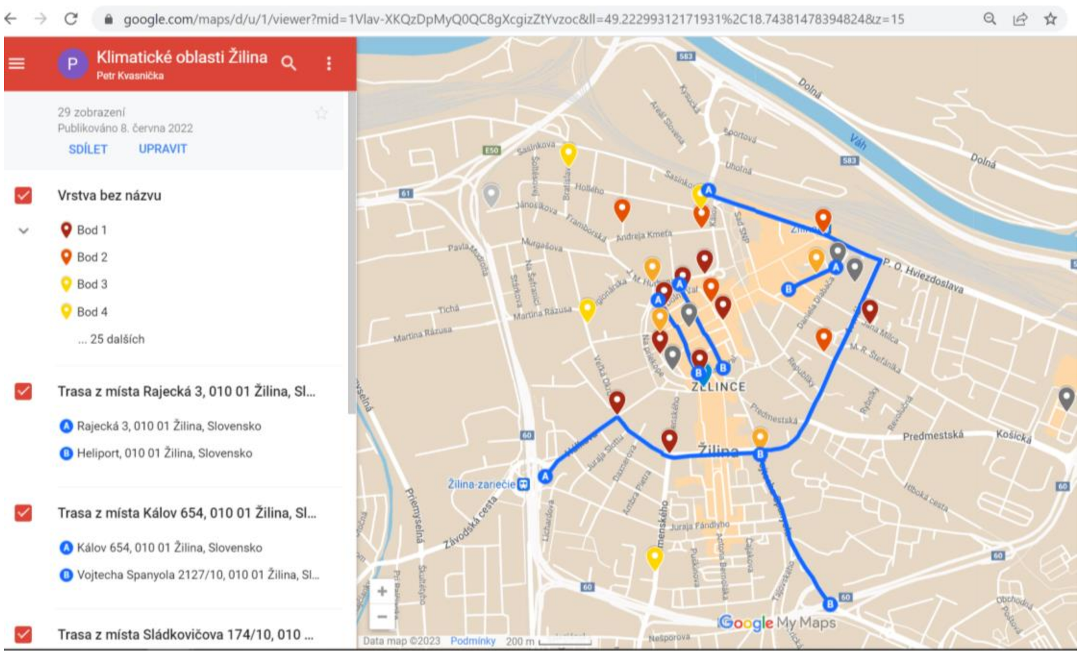


Figure 14: Preparing for local heat island measurements

The map is available at: https://www.google.com/maps/d/u/1/viewer?mid=1Vlav-XKQzDpMyQ0QC8gXcgizZtYvzoc

Characteristics have been added for each location according to the available data.

Listing of locations

POINT 1

- Street name: J. M. Hurbana
- NDVI min: 0
- NDVI max: 7
- Street width:
- Building Height:
- Wind flow: Open to one wind flow (Sharp angle)
- Orientation: West - South
- Cars per day: 3000
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: High

POINT 2

- Street name: Andreja Kmet'a
- NDVI min: 0
- NDVI max: 28
- Street width:
- Building Height:
- Open
- Orientation: West
- Cars per day:
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: Medium.
- Remarks: The western part of the street has a better NDVI

POINT 3

- Street name: Hollého
- NDVI min: 5
- NDVI max: 18
- Street Width:
- Building Height:
- Wind flow: partially blocked east
- Orientation: West
- Cars per day:
- People Movement Intensity:
- Population: 8,900 (Old Town)
- Risk: Medium-low.

POINT 4

- Name.
- Street name: Komenského
- NDVI min: 28
- NDVI max: 32
- Street Width:
- Building Height:
- Wind flow: Open.
- Orientation: South
- Cars per day: 10,000
- Intensity of people movement:
- Population: 1606 + 1491 (Hliny VIII + Hliny III)
- Risk: Low (Air quality risk higher)
- Remarks: The school has a higher air quality risk

POINT 5

- Name: Crossroads
- Street name: Hálkova - Velká Okružná
- NDVI min: 5
- NDVI max: 23
- Street Width:
- Building Height:
- Wind flow: Open
- Orientation: Southwest
- Cars per day: 16,000
- Intensity of people:
- Population: 305+ 8,900 (Little Prague + Old Town)
- Risk: High
- Remarks: Open area (High daily temperatures)

POINT 6

- Name: Crossroads
- Street name: Velká Okružná - Komenského
- NDVI min: 8
- NDVI max: 13
- Street width:
- Building Height:
- Wind flow: Open
- Orientation: West - South
- Cars per day: 10,000 - 15,000
- Intensity of people movement:
- Population: 305 + 838 + 8,900 (Mala Praha +Hliny I +Staré mesto)
- Risk: High
- Remarks: Open area (High daily temperatures)

POINT 7

- Name: Centre of the square
- Street name: Marianské námestie
- NDVI min: No info
- NDVI max: No info
- Street Width:
- Height of buildings:
- Wind flow: Closed
- Orientation: Southeast
- Cars per day:
- Intensity of people movement: High
- Population: 8,900 (Old Town)

- Risk: Medium - High
- Remarks: Open area (High daytime temperatures)

POINT 8

- Name: Bus Station
- Street Name:
- NDVI min: 0
- NDVI max: 20
- Street Width:
- Building Height:
- Wind flow: Closed
- Orientation: Southwest
- Cars per day: 10,000
- Intensity of people movement: High
- Population: 8,900 (Old Town)
- Risk: Medium-low (air quality)
- Remarks: Open area (High daytime temperatures)

POINT 9

- Name: Aupark Žilina (Sever)
- Street name: Romualda Zaymusa
- NDVI min: 0
- NDVI max: 18
- Street width:
- Building Height:
- Wind flow: partially closed east.
- Orientation: South
- Cars per day:
- Intensity of people movement: High
- Population: 8,900 (Old Town)
- Risk: High
- Remarks: the reference measurement site

POINT 10

- Street name: Bratislavská
- NDVI min: 0
- NDVI max: 7
- Street width:
- Height of buildings:
- Wind flow: closed south
- Orientation: South

- Cars per day:
- Intensity of people movement: Low
- Population: 8,900 (Old Town)
- Risk: Low

POINT 11

- Street name: Radlinského
- NDVI min: 2
- NDVI max: 5
- Street width:
- Building Height:
- Wind flow: partially closed south
- Orientation: South
- Cars per day:
- Intensity of people movement: Low.
- Population: 8,900 (Old Town)
- Risk: Medium

POINT 12

- Name: End of Street (West)
- Street name: Janošíková
- NDVI min: 7
- NDVI max: 10
- Street Width:
- Building Height:
- Wind flow: Open
- Orientation: West
- Cars per day:
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: Medium.
- Remarks: Industrial + shops

POINT 13

- Street name: Velká okružná
- NDVI min: 0
- NDVI max: 30
- Street Width:
- Building Height:
- Wind flow: Open
- Orientation: South

- Cars per day: 5000
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: Low
- Remarks: Very small street area

POINT 14

- Name: Crossroads
- Street name: J. M. Hurbana + Kuzmányho
- NDVI min: 3
- NDVI max: 10
- Street width:
- Building Height:
- Wind flow: Closed from the west and north
- Orientation: West + South (no North)
- Cars per day: 3000
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: Medium.

POINT 15

- Hub 1
- Street name: Dolný Val + Sládkovičova
- NDVI min: 0
- NDVI max: 10
- Street width:
- Building Height:
- Wind flow: Open from the north
- Orientation: southeast
- Cars per day:
- Intensity of people movement: High
- Population: 8,900 (Old Town)
- Risk: High
- Remarks: Enclosed area (High night temperatures), possibility of green space

POINT 16

- Name: hub 2
- Street name: Dolný Val + Hodžova
- NDVI min: 0
- NDVI max: 0
- Street width:

- Height of buildings:
- Wind flow: Closed
- Orientation: Southeast
- Cars per day:
- Intensity of people movement: High.
- Population: 8,900 (Old Town)
- Risk: High
- Remarks: Enclosed area (High night temperatures), possibility of landscaping, parking lot

POINT 17

- Name: Hub 3
- Street name: Horný Val
- NDVI min: 1
- NDVI max: 4
- Street width:
- Building Height:
- Wind flow: Closed
- Orientation: South
- Cars per day:
- Intensity of people movement: High.
- Population: 8,900 (Old Town)
- Risk: High
- Remarks: Enclosed area (High night temperatures), possibility of green space modifications

POINT 18

- Name: Church
- Street name: Horný Val + Farská ulička
- NDVI min: 0
- NDVI max: 0
- Street Width:
- Building Height:
- Wind flow: Open from the west
- Orientation: South
- Cars per day:
- Intensity of people movement: High.
- Population: 8,900 (Old Town)
- Risk: Medium - High
- Remarks: (High daytime temperatures)

POINT 19

- Name: Middle of the square
- Street name: Horný Val
- NDVI min: 0
- NDVI max: 0
- Street Width:
- Building Height:
- Wind flow: partially enclosed
- Orientation: West.
- Cars per day:
- Intensity of people movement: High
- Population: 8,900 (Old Town)
- Risk: High
- Remarks: Close to the measured area.

POINT 20

- Name.
- Street name: Horný Val
- NDVI min: No info
- NDVI max: No info
- Street Width:
- Building Height:
- Wind flow: Closed.
- Orientation: South
- Cars per day:
- Intensity of people movement: High.
- Population: 8,900 (Old Town)
- Risk: Medium - High
- Remarks: Open area (High daytime temperatures)

POINT 21

- Name: Hub 3
- Street name: Dolný Val
- NDVI min: 0
- NDVI max: 0
- Street Width:
- Building Height:
- Wind flow: Closed
- Orientation: South
- Cars per day:
- People Movement Intensity:
- Population: 8,900 (Old Town)

- Risk: High
- Remarks: Enclosed area (High night temperatures), possibility of green space modifications

POINT 22

- Name: Hub 4
- Street name: Jana Kalinčiaka + Dolný Val + Jesuitská
- NDVI min: 2
- NDVI max: 9
- Street width:
- Building Height:
- Open west + partially open east
- West + South
- Cars per day:
- Intensity of people movement: High
- Population: 8,900 (Old Town)
- Risk: Medium
- Remarks: Enclosed area (High night temperatures), possibility of green space modifications

POINT 23

- Name: Crossroads
- Street name: Velká Okružná + Vojtecha Spanyol
- NDVI min: 21
- NDVI max: 26
- Street width:
- Building Height:
- Wind flow: Open
- Orientation: Southeast
- Cars per day: 15,000 - 20,000
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: Medium
- Remarks: Open area (High daytime temperatures)

POINT 24

- Name: Moyzesova Street (western part)
- Street name: Moyzesova
- NDVI min: 3
- NDVI max: 7
- Street width:
- Building Height:
- Wind flow: Closed

- Orientation: West
- Cars per day:
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: Medium - High

POINT 25

- Name: Crossroads
- Street name: Daniela Dlabača + Vojtecha Tvrdého
- NDVI min: 0
- NDVI max: 0
- Street width:
- Building Height:
- Wind flow: Open South.
- Orientation: South
- Cars per day:
- Intensity of people movement:
- Population: 8,900 (Old Town)
- Risk: Medium - High
- Remarks: Open area (High daytime temperatures), vegetation management.

POINT 26

- Street name: Vojtecha Tvrdého
- NDVI min: 0
- NDVI max: 28 (end of street towards the square)
- Street width:
- Height of buildings:
- Wind flow: closed
- Orientation: Southwest
- Cars per day:
- People Movement Intensity:
- Population: 8,900 (Old Town)
- Risk: Medium.

POINT 27

- Name: Train station
- Street name: P. O Hviezdoslava
- NDVI min: 0
- NDVI max: 0
- Street width:
- Building Height:

- Wind flow: Open
- Orientation: West.
- Cars per day: 10,000
- Intensity of people movement: High
- Population: 8,900 (Old Town)
- Risk: High
- Remarks: Open area (High daytime temperatures), air quality

POINT 28

- Street name: Jána Milca
- NDVI min: 10
- NDVI max: 15
- Street width:
- Height of buildings:
- Wind flow: Partially closed
- Orientation: Southwest
- Cars per day:
- Intensity of people movement: High
- Population: 8,900 (Old Town)
- Risk: Medium - High

POINT 29

- Name: TESCO
- NDVI min: 0
- NDVI max: 10
- Street Width:
- Building Height:
- Wind flow: partially enclosed
- Orientation: South
- Cars per day:
- Intensity of people movement: High.
- Population: 8,900 (Old Town)
- Risk: Medium
- Remarks: Open area (High daytime temperatures)

Conclusions from measurements

The city centre requires attention regarding climate change impacts and parking regulation, as there are many locations at risk of climate change impacts. In revitalization projects, we recommend deploying sensors to record pre- and post-investment values. This is primarily a network of weather stations, surface and subsurface temperature sensors, air quality indicator sensors, traffic sensors and pedestrian counting sensors. The data collected will not only influence the effective design of the city centre revitalisation, but also the retail sector by creating pleasant places to live, purposefully connected by green corridors. It will also generate interest in measures to address climate change, efficient deployment of RES and sustainable transport.

Table 6: Summary of recommended deployment of sensors for measuring heat islands and environmental quality

Location A Sládkovičova	Meteostation
Location B Jána Kaliničáka	Meteostation
Location C Tržiště	Meteostation + PM + NOx
Location D Hodžova	Meteostation
Location E Katedrála a Namiestie A. Hlinky	Meteostation
Location F Pernikárska	Meteostation + surface and under surface temperature
Location H Vlakové nádraží	Meteostation + PM + NOx
Location I Autobusové nádraží	Meteostation
Location K Velká okružná-Hálkova	Meteostation + PM + NOx

Note: Meteostation, i.e. measurement of air temperature at 2m and 80cm, humidity, atmospheric pressure, wind power and direction.

Annex 2: Wind flow assessment

Introduction

Wind speed is affected by obstacles that block wind flow. Wind flows are defined by street corridors. The greater the width of the street, the better the wind flow. These ventilation nodes are not the only source of wind. If the wind flow hits an obstruction, part of the flow is diverted to higher layers (above the roof of the building). An illustration of this phenomenon is shown in the figure below. Simplistically, if the width between buildings is small, the airflow enters the street and the wind speed in the street is reduced. If the distance between buildings is large enough, the airflow is allowed to stabilize at full force. Full recovery of the air current occurs when the distance from the building is approximately 2 to 3 times the height of the building that the air current has impacted. In addition, if there is another obstacle in the way (e.g., a tree canopy), this obstacle may increase the distance for the airstream to recover. This phenomenon can be observed at the meteostation Sad na Studničkách, where no air current is detected from the west direction. The air current is reflected from the town hall to the higher layer and on recovery the air current bounces back from the treetops.

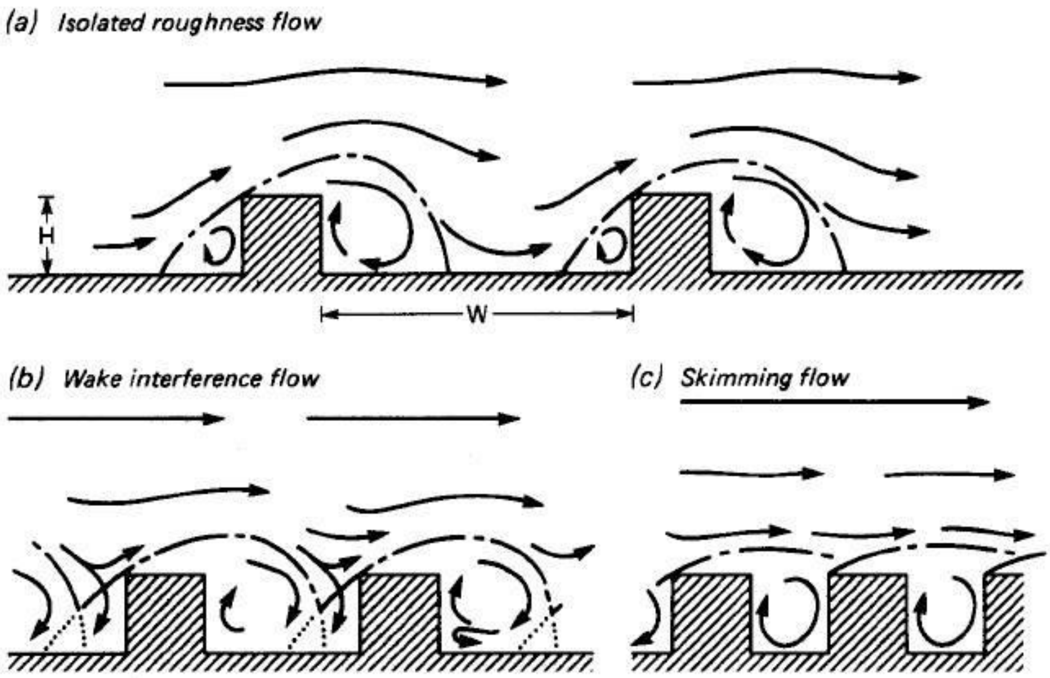


Fig. 1. The flow regimes associated with air flow over building arrays of increasing H/W.

Figure 15: Behaviour of air currents [10]

With respect to wind flow, selected locations were investigated for which the width and height of the buildings and the distances between the various obstacles to wind flow were considered.

Location A

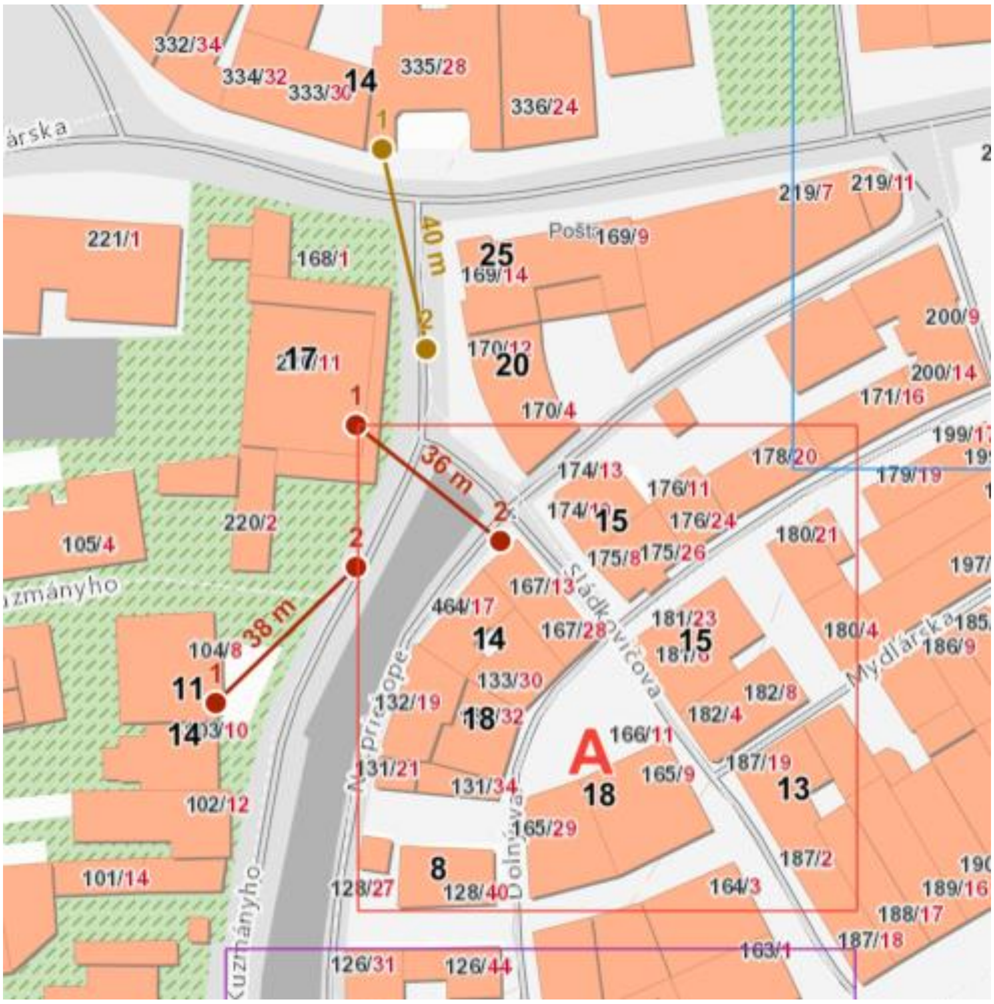


Figure 16: Location A

At Location A, it can be seen that the building heights (indicated by the black numbers) prevent the air currents from resuming in the area. The main influence is in the area of the car park around Dolný val and Sládkovičova Street. In the case of the area of the northern part between Kuzmányho and Na Prikope it can be observed that the wind flow has a chance to resume from the north side and west-south side. The northern side can be used to lead the air artery to the city centre. It is recommended to increase the level of vegetation on Sládkovičova Street and to further consider the deployment of a meteo station on Sládkovičova Street.

Location C

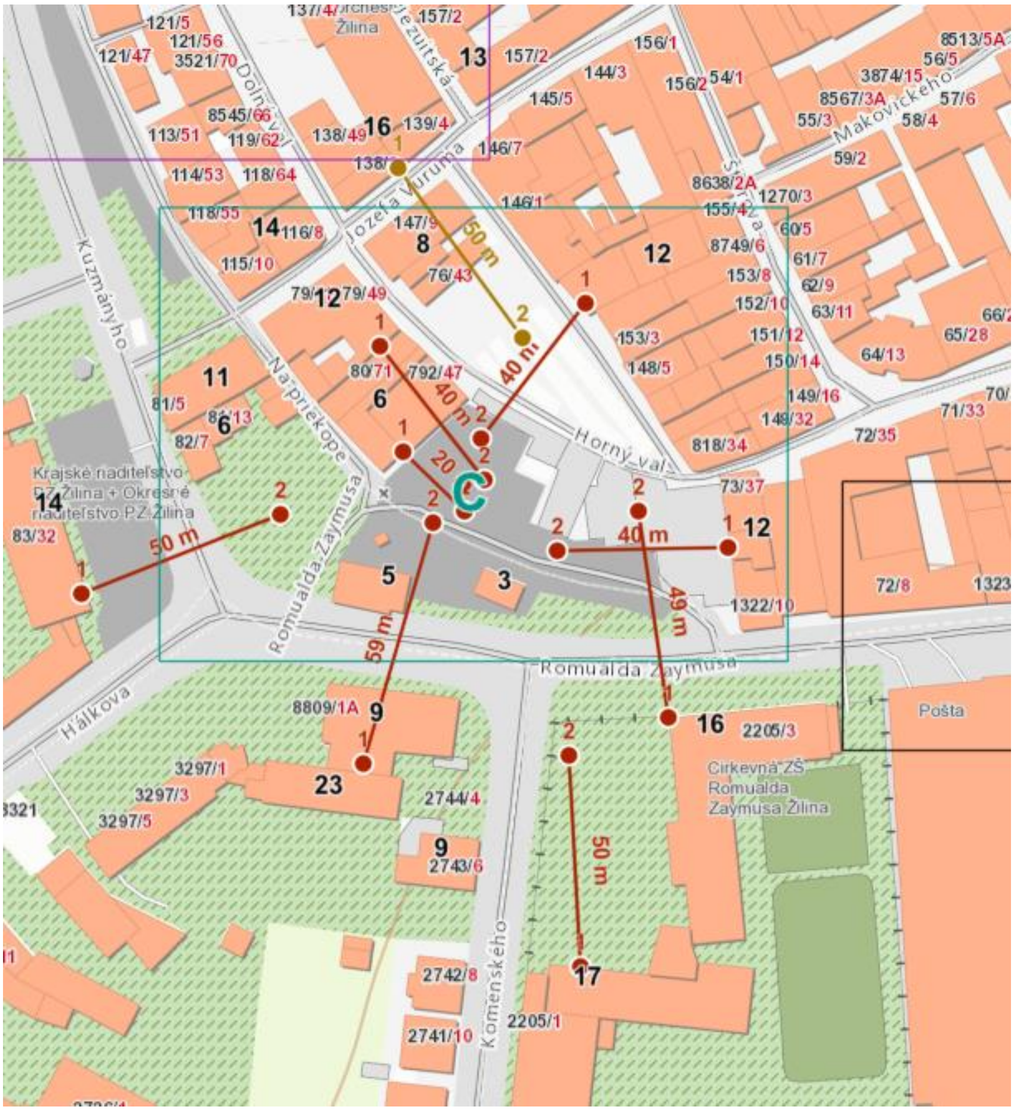


Figure 17: Location C

From the wind analysis of Location C (Marketplace), it can be observed that the area has very good chances of renewed wind flow from the south, southwest and partly from the west. The disadvantages of this location are that there is no direct corridor into the town centre. The influence of any vegetation will be felt on the west side of the centre across Horný val in the case of a southerly flow. The marketplace will impact the south side of town via the southern portion of Upper Mound Street. If the wind flow is south-westerly, the impact on the centre of the city centre will be minimal due to the indirect corridor into the city, with some of the airflow largely reflecting off adjacent buildings and subsequently 'overflying' the city centre.

There is an increased risk of reduced air quality due to increased traffic density at Hálkova and Komenského Streets.

Location J

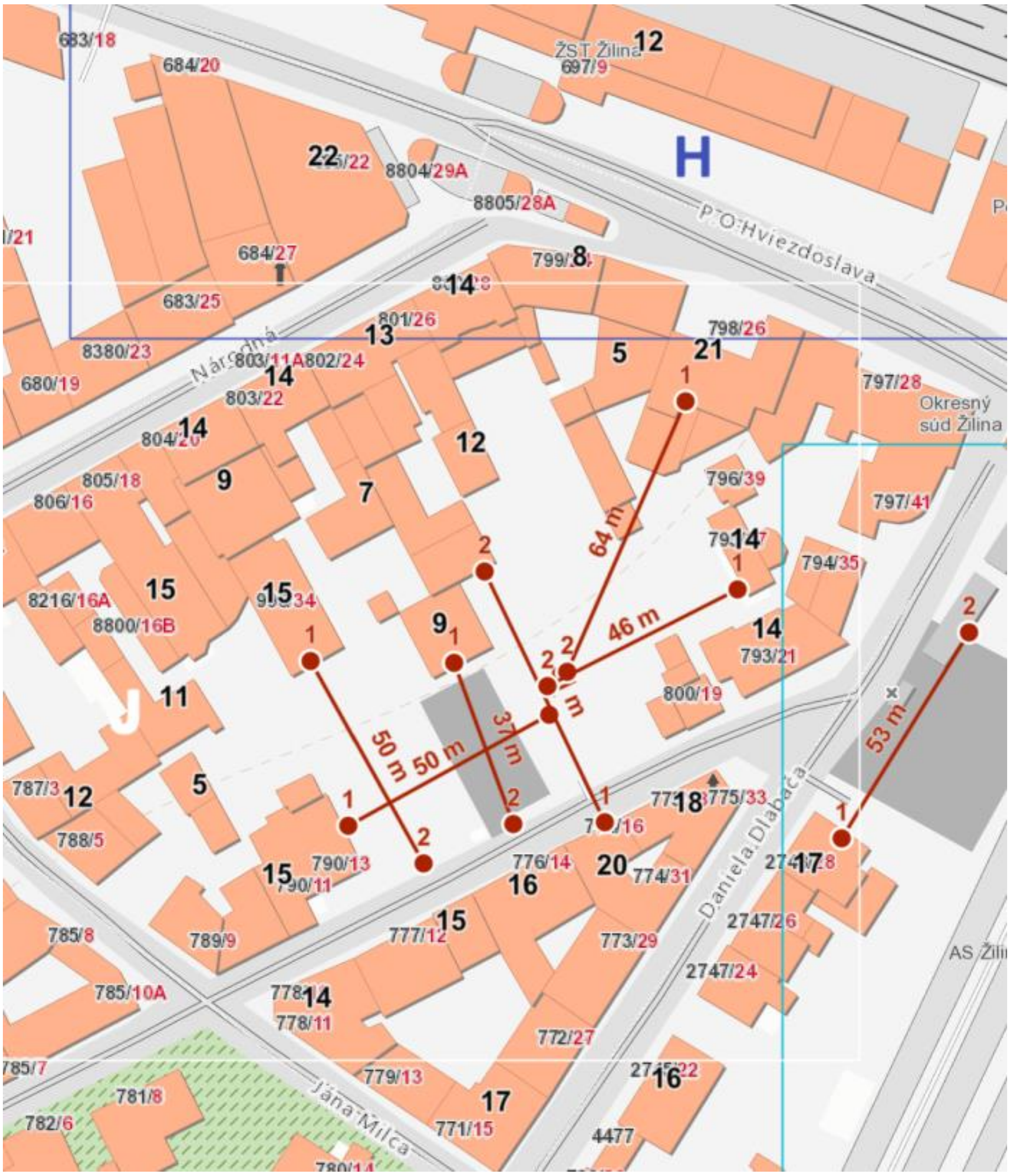


Figure 18: Location J

The area around the car park is enclosed from the north-west and south. The parking lot has a chance to recover wind flow from the north and northeast. It would be appropriate to shade the parking lot with trees or other roofing methods. It is recommended that taller vegetation be planted on the south side of the parking lot; due to the tall buildings on the south side, there will be no threat of blocking the air flow. The buildings on the south prevent wind flow. The parking lot has negative impacts on the citizens due to its proximity to residential homes.

Location Sad na Studničkách

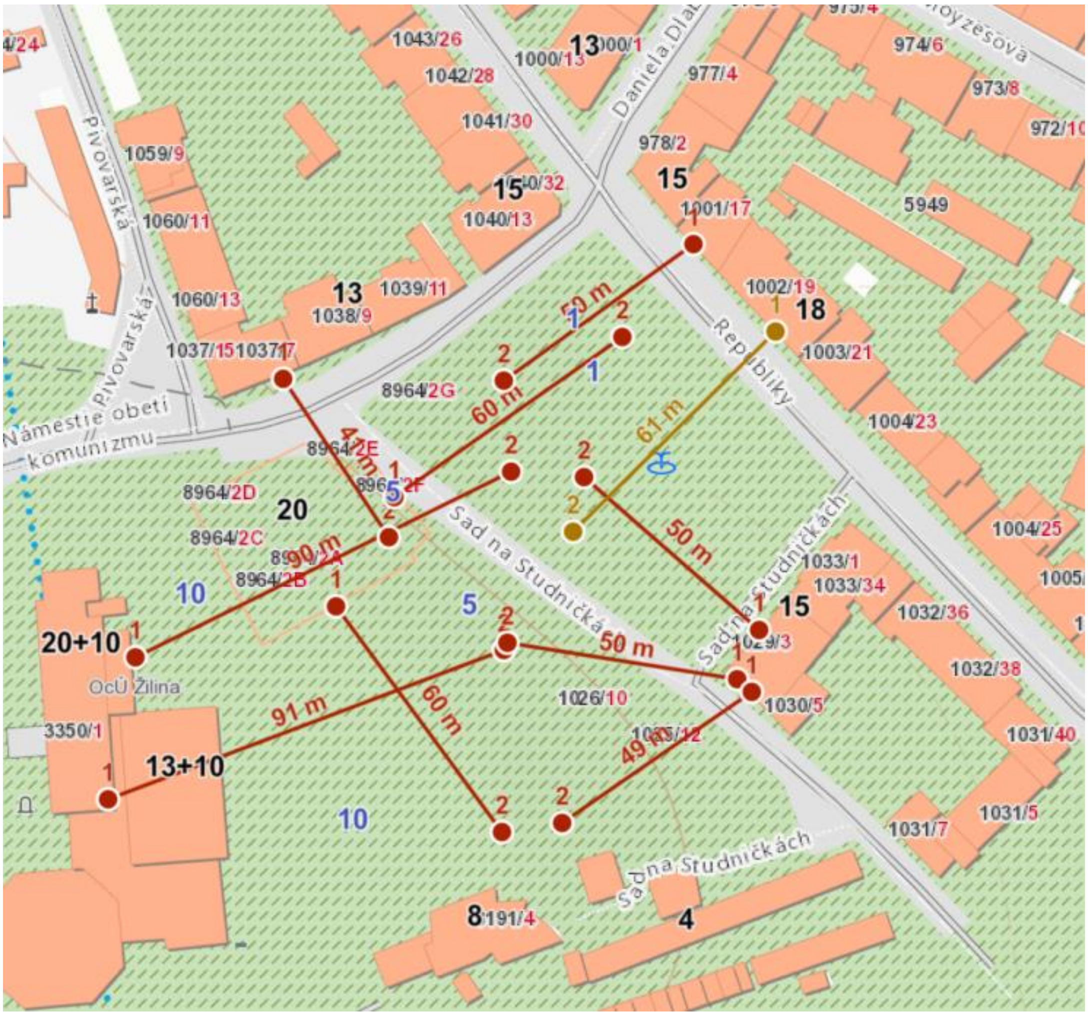


Figure 19: Location Sad na Studničkách

The measured location Sad na Studničkách is a public park with a high density of taller vegetation that is located in a small hill, the steepness of the hill is shown by the blue numbers. The Town Hall area is elevated approximately 10 m. In the case of wind movement, this fact means that the town hall from the park view is 30 m high. A westerly wind flow that passes over the town hall can settle at a worst case scenario up to 90 m from the town hall. Furthermore, it is important to note that there is tall vegetation in the park, which consequently increases the distance at which the wind reaches the ground. The phenomenon can be observed in the graph "Frequency of wind speed on wind direction Sad vs Aupark".

The approach of the southern part of the park to the wind is well guided, as there are objects with a small height (approximately up to 4 to 8 m). The eastern side is blocked by buildings with a height of around 18 m, in any case the buildings are no longer elevated.

Location Aupark

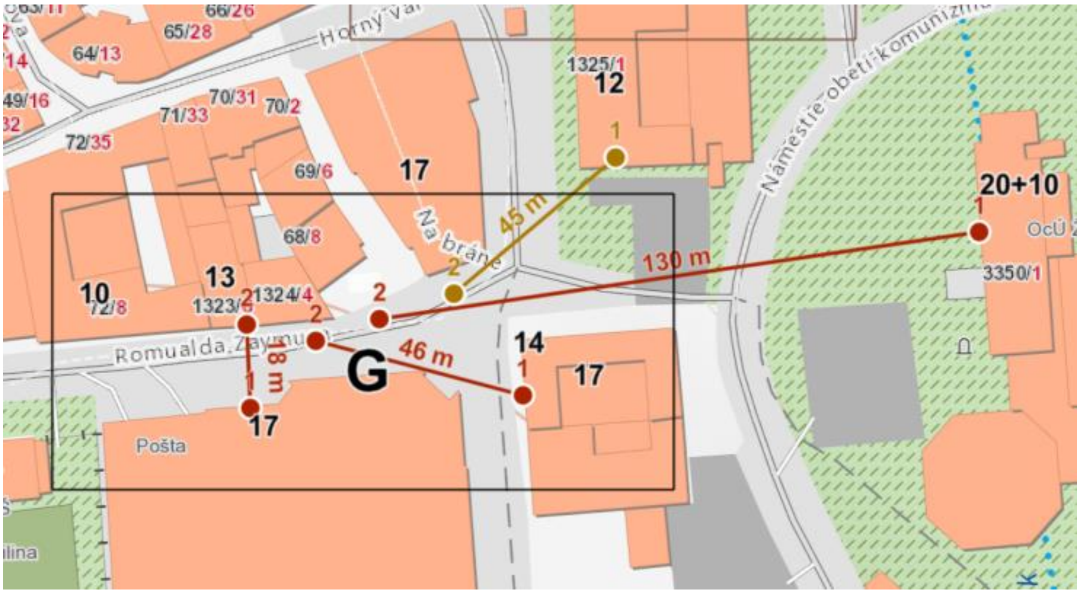


Figure 20: Aupark location

In the measured Aupark location it can be observed that the west and east are not blocked by any obstacle, thus these directions should have relative wind speeds. This fact can be observed in the graph "Frequency of wind speed on wind direction Sad vs Aupark", where it can be seen that the speeds in the west and east directions are significant. The south and north directions are completely isolated, and if the wind flow is in one of these directions, the speed should be drastically reduced. This feature is also observable from the graph. It can also be seen that the new town hall has no effect on the wind flow, as it is approximately 130 m away from Aupark.

Wind flow statistics

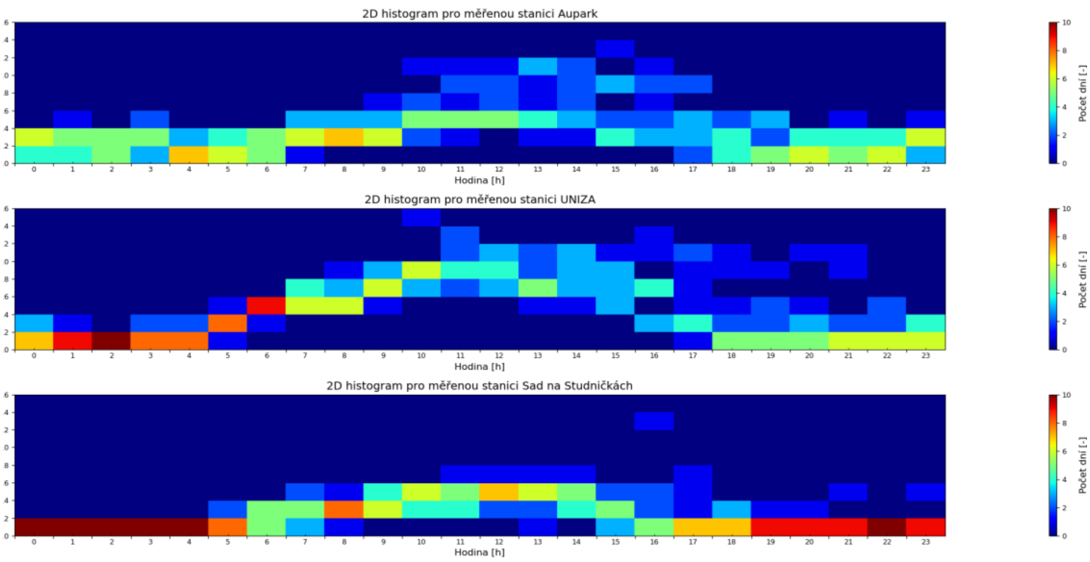


Figure 21: Analysis of wind strength and direction at maximum temperatures above 30 °C at 2 m height for the month of July 2022 ("Max_Temperature_200cm_more_30_C_histogram_M__7")

DESCRIPTION:

In Figure 21, a 2D histogram is produced. The histogram gives the frequency of occurrence of wind speed for a specific hour at all measured stations.

- The wind speeds are averaged over one hour.
- The days that were selected correspond to tropical days (daytime temperatures exceeding 30 °C) at the Aupark weather station for the month of July. The temperature is measured at a height of 2 m above the ground.
- The total number of tropical days for the month of July was 10 days.

OBSERVATIONS:

- From the histogram, it can be observed that the wind speed is drastically reduced during the night hours. When comparing the Aupark locations with the Sad na Studničkách, differences in night and day wind speeds can be observed. During nighttime hours, the flow is more intense at Aupark than at Sad na Studničkách.
- In the afternoon, the wind speed in Aupark is twice as strong as in the adjacent Sad na Studničkách.

REASONS:

- The difference in wind speeds can be explained by the presence of tall vegetation in the Sad na Studničkách.
- Another reason is the influence of the surrounding buildings around the orchard which create a wind shield. These buildings, due to their height, prevent air access, this influence can be observed in the graph "Frequency of wind speed and wind direction".

Trends in wind direction

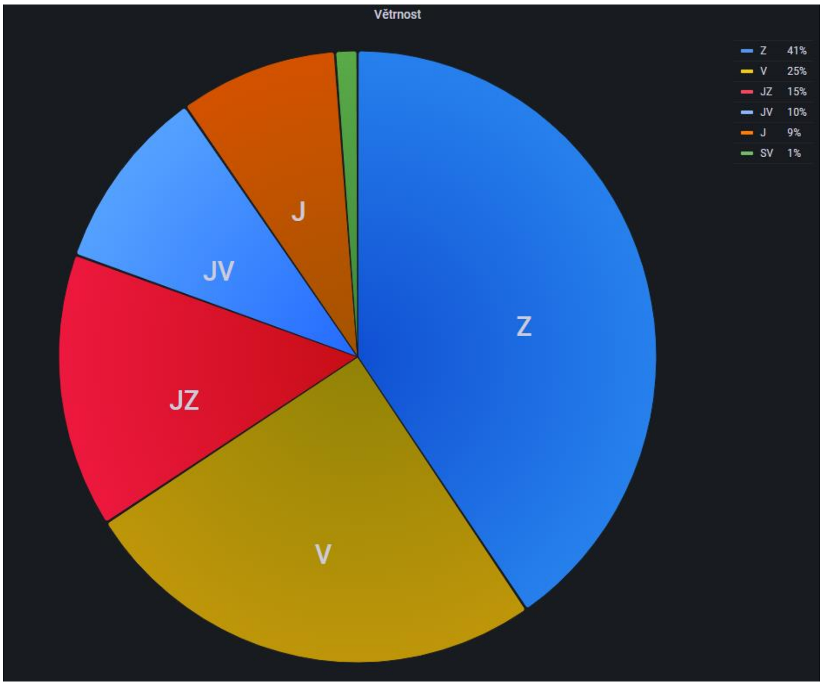


Figure 22: Aupark site, summer 2022, wind flow pattern; Westerly winds (Z) account for 66%

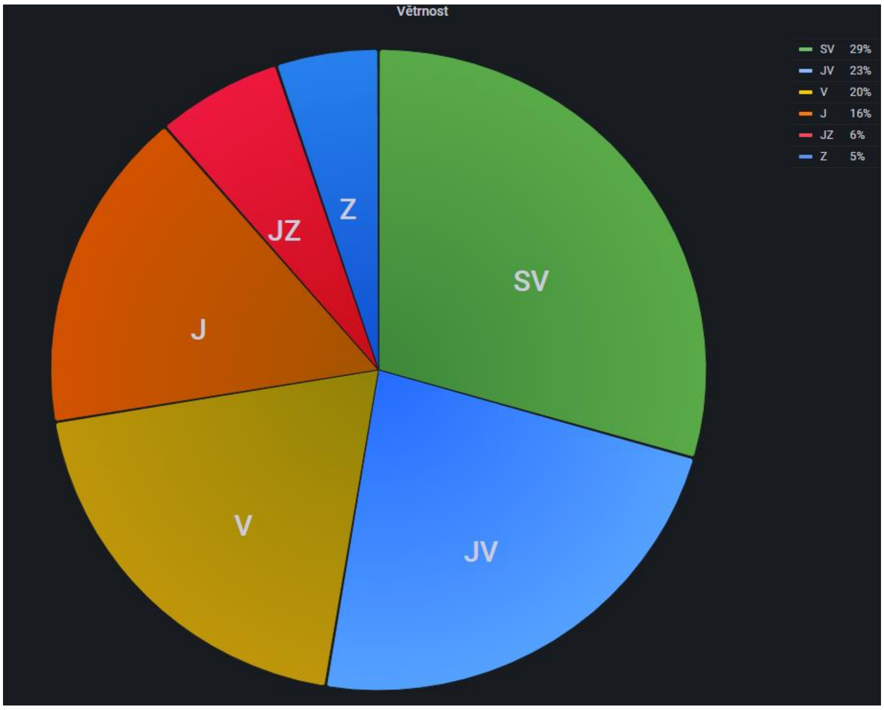


Figure 23: Sad na Studničkách site, summer 2022, wind flow pattern; easterly winds (V) account for 72%.

Annex 3 Assessment of ice and frost formation at UNIZA

Introduction

Ice and frost are physical phenomena that form ice surfaces. These icy surfaces subsequently form hazardous areas where pedestrians can be injured or cause automobile accidents. The physical phenomenon of icing is defined by the formation of ice caused by residual water left over from rain or melted snow. The phenomenon begins to occur when air and surface temperatures drop below 0 °C. Ice can be inferred using measured air, surface and precipitation temperatures. A different phenomenon that causes surface freezing is called ice accretion (rime). The condition where air and surface temperatures are below zero is the same as for icing. The main difference is in the generation of water. Frost/rime is formed by condensation of water. Water condenses because of the temperature difference between the air and the surface, i.e., when the surface is colder than the ambient air temperature and the humidity is close to saturation. The air is unable to hold the moisture and thus water begins to form on the surface. If the surface temperature is below 0 °C, the condensed water subsequently turns into slippery ice.

Evaluation

For the evaluation of the ice and frost phenomenon, the period December 2021 was chosen. The location around the UNIZA University was used for the measurements. The measurement components included a meteo station, a surface and subsurface temperature sensor, and the online weather service Tomorrow.io, which provided cloud cover and precipitation data. Contact observations were also made with the selected area. The observed phenomena were ice formation on the sensor, pavement, road, and if there was snow residue in the area. The results are presented in the table.

Table 7: Analysis and evaluation of the occurrence of ice and frost in December 2021

Date	Time	Deduced			Observed			
		Snow	Icing	Frost	Sensor	Pavement	Road	Snow
01.12.2021	4:00	X	X		X	X	X	X
05.12.2021	3:00	X	X					
06.12.2021	8:00	X						X
08.12.2021	18:00			X				
09.12.2021	7:00	X		X				
10.12.2021	18:00		X					
13.12.2021	22:00		X	X	X	X	X	

20.12.2021	6:00	X						X
21.12.2021		X						X
25.12.2021	11:00	X	X					
28.12.2021	15:00		X					

The table lists the phenomena that were deduced in the introduction. The contact observations for December were made from December 1, 2021 to December 21, 2021 and weekends were omitted. Icing occurred in early December, which was caused by rain and partial snowfall that took place during the night hours. Heavy snowfall occurred between 5.12 - 6.12. The first icing was observed on 8.12 when it formed during the night hours and then in the morning hours of the following day (9.12). On the same day it started to snow. This snow melted during the day on 10.12 and the residual water froze during the night hours. On 13.12, frost formed during the night hours. Heavy snowfall occurred between about 20.12 and 21.12, which produced snow that lasted until the end of New Year's Eve. Ice formed during this period on 25.12 and 28.12 when air temperatures got above 0 °C during the day, these temperatures subsequently melted the snow and the water froze on those days. The total number of days when icing occurred was 6 days and for frost it was 3 days.

Examples of frost and ice are shown in the figures below. In the first graph of Figure 24, areas where the surface temperature is colder than the air temperature are shown in colour.

Colour indication:

- **Red** - surface temperature colder than air temperature and air temperature less than 0 °C
- **Yellow** - surface temperature is close to air temperature and air temperature is less than 0 °C
- **Green** - surface temperature is approaching air temperature and air temperature is greater than 0 °C
- **Blue** - surface temperature is cooler than air temperature and air temperature is greater than 0 °C

The dashed vertical lines indicate the time at which the location was observed. At the bottom of these lines the phenomena that were observed are listed.

- S - Remnants of snow or snowfall
- R - Ice was observed on the road
- C - Ice was observed on the pavement
- D - Ice was observed by a measuring device

The second graph in Figure 24 shows the values of humidity, cloud cover and precipitation. Cloud cover and precipitation are obtained using the Tomorrow.io web service.

Colour indication:

- **Red** - humidity above 95%
- **Yellow** - humidity greater than 80%

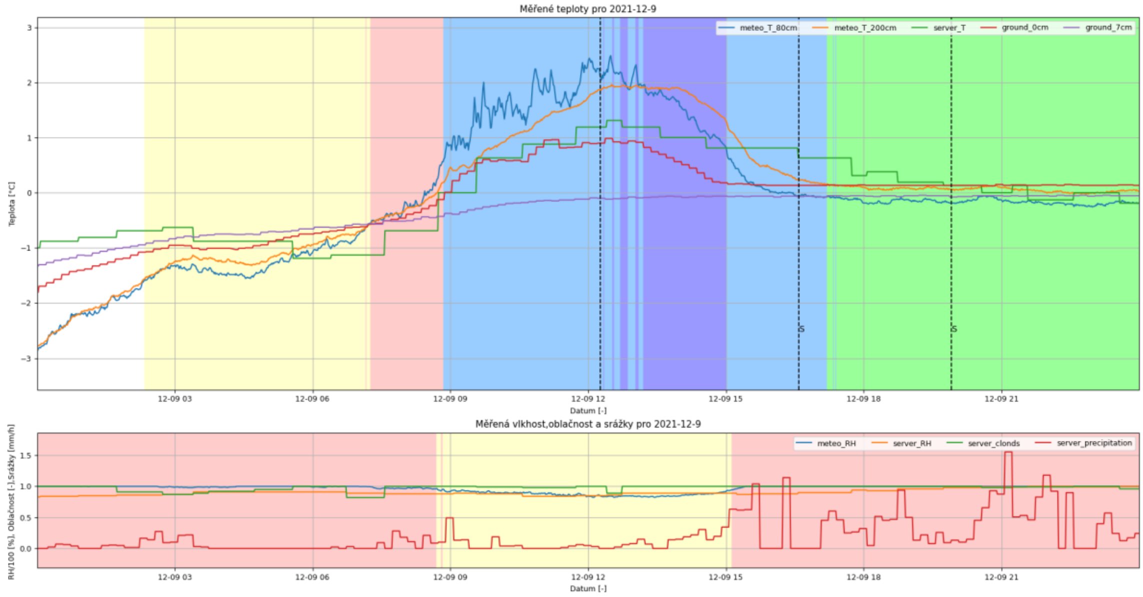


Figure 24: Frost event from 9.12.2021

The frost formed briefly in the morning hours when the air temperature was warmer than the measured surface temperature and the humidity was greater than 95%.

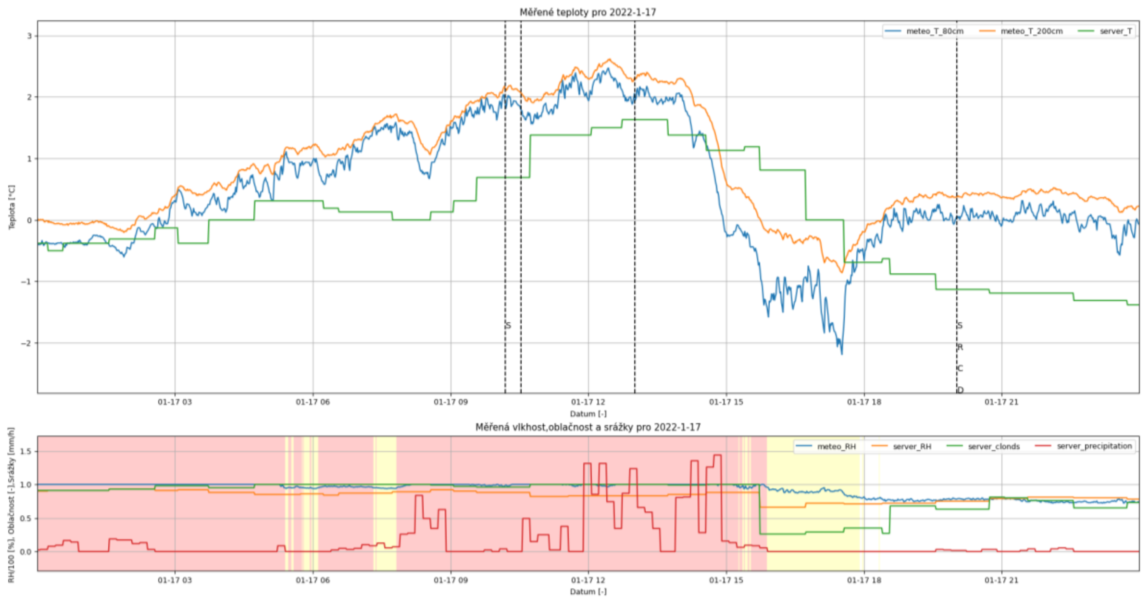


Figure 25: Ice event from 17.01.2022

The icing formed in the evening due to persistent rain in the afternoon.

Annex 4 Technical background and limits of the technologies used

Internet of Things (IoT) sensor networks are a global trend for more efficient management of various public and private sector agendas. Continuous and long-term monitoring of specific phenomena creates the necessary data base for the use of machine learning and artificial intelligence. The current limitations are mainly in the lack of coverage (only one phenomenon is monitored for a specific service, e.g. the temperature of a private carrier's freezer) or sector-oriented deployment (e.g. remote readings of a specific operator's energy distribution network).

The CleverNet project addressed both the conceptual deployment of sensor networks and the technical advantages or limitations of deployed networks. In the area of conceptual grasp, a handbook for digital spatial planning was produced, which is seen as a cross-departmental/ holistic approach to the development of sensor networks and the digital economy. In the area of technical advantages and limitations, both the operational economics and the HW and SW characteristics of the deployed network were investigated.

Conceptual deployment of sensor networks

Digital spatial planning is a digital economy concept whose primary objective is to help streamline the processes associated with land development, i.e., zoning and construction management and the limits/threats of unsustainable projects and developments. It thus encompasses 4 key areas where the application of sensor networks is perceived as critical:

- Energy and RES development,
- water management and water availability in the landscape,
- transport and logistics
- Climate conditions and climate change

All these areas determine the feasibility of investments in the territory (e.g. sufficient energy supply, sufficient water supply, transport connections...) and the availability of this information is critical for the development of any territorial unit. Sensor networks are deployed on a single purpose basis (e.g. for the energy network) and the information is not shared or linked to other fields, which however primarily affect the efficiency in question, e.g. the intensity of direct solar radiation has an impact on RES energy production, which impacts on the stability of the energy network in the current massive RES development. Thus, for the conceptual deployment of sensor networks, a comprehensive overview of the agendas for which data support/digitization is crucial has been developed.

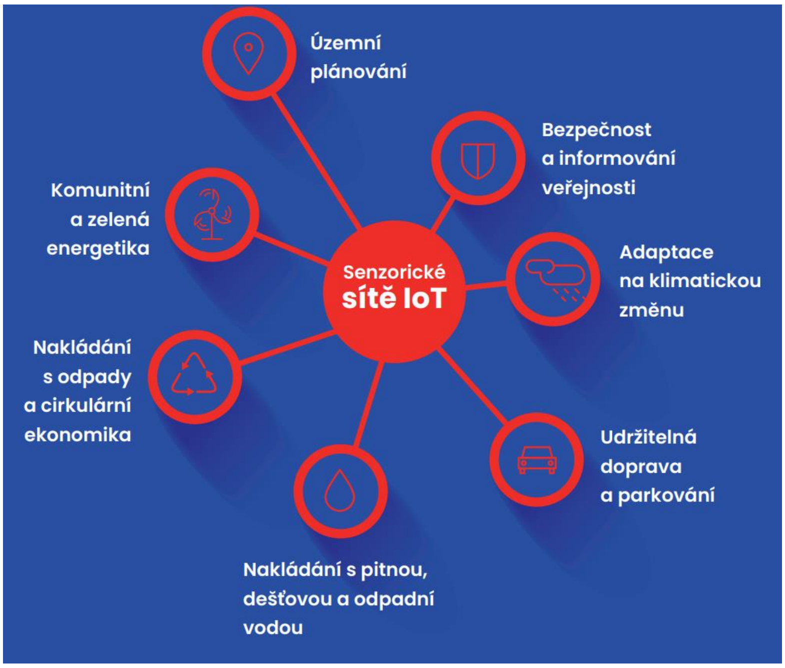


Figure 26: Overview of the main agendas that require digital transformation

A set of sensor networks has been compiled for each agenda, which are individually already in use but lack a conceptual approach to digitalisation. Thus, individual use cases were also linked to the proposal of subsidy support for network development by different ministries (applied to the Czech environment).

	OBOR	PŘÍPAD UŽITÍ	SENZORY	AGENDA	SPRÁVCE DOTAČ. TITULU
Základní senzorická síť pro obce všech velikostí	BEZPEČNOST A KONEKTIVITA	Digitalizace krizového řízení Konektivita IoT	CITYWAN	Digitalizace veřejných služeb	Ministerstvo pro místní rozvoj Ministerstvo vnitra
	KLIMA	Adaptace na klimatickou změnu	Meteostanice Senzory teploty povrchu Pyranometr Srážkoměr	Digitalizace veřejných služeb	Ministerstvo pro místní rozvoj Ministerstvo životního prostředí
	DOPRAVA	SUMP Dopravní generel	Senzory dopravní intenzity	Digitalizace veřejných služeb	Ministerstvo pro místní rozvoj
	ENERGETIKA	Územní energetická koncepce	Dálkové odečty spotřeby energií, tepla a plynu Dálkové odečty vyrobené energie z FVE	Digitalizace veřejných služeb	Ministerstvo pro místní rozvoj
	VODA	PRVKÚK a ČOV	Dálkové odečty spotřeby pitné vody Dálkové řízení ventilů (u obcí postižených suchem) Stav čerpacích stanic VHI	Digitalizace veřejných služeb	Ministerstvo pro místní rozvoj
	ODPADY	Cirkulární ekonomika Digitalizace sběru a svozu	Vážení na svozovém vozidle, nebo Senzory naplněnosti kontejnerů	Digitalizace veřejných služeb	Ministerstvo pro místní rozvoj
Rozšířená senzorická síť pro obce s rozšířenou působností	DOPRAVA	SUMP	Senzory sčítání chodců, cyklistů a cestujících v MHD (včetně alternativy trackování)	Digitální podpora SUMP	Ministerstvo dopravy
	VODA	Modrozelená infrastruktura a dešťová voda	Hladinoměry dešťových nádrží Hladinoměry řek Senzory vlhkosti půdy	Digitalizace modrozelené infrastruktury	Ministerstvo životního prostředí
	ŽIVOTNÍ PROSTŘEDÍ	„Akční plán kvality ovzduší Hluková mapa“	Senzor prachových částic Senzor oxidu dusíku Hlukoměry Senzory vnitřního prostředí veřejných budov	Digitalizace kvality prostředí	Ministerstvo životního prostředí
	VODA/ ENERGETIKA	Energetický benchmarking čistíren odpadních vod	Dálkové odečty ČOV	Digitalizace odpadních vod	Ministerstvo životního prostředí
	VODA	Odpadní voda	Senzory COVID19 a drog	Digitalizace odpadních vod	Ministerstvo životního prostředí

Figure 27: Linking sensor network use cases to potential subsidy programmes

Technical parameters of the network and sensors

The CleverNet project focused on the link between the areas of transport and climate change; in simple terms, the effects of transport and transport infrastructure, primarily concrete or asphalt surfaces, on the microclimate and heat islands in the city. For the purpose of data analysis, it has thus created dashboards, freely available to the wider professional or lay public:

Figure 28: Overview of open data dashboards built to explore specific use cases

- **Traffic dashboard** available at https://dashboards.clevernet.sk/d/-ewuYuM7k/traffic?orgId=1
- **Heat island dashboard**, available at https://dashboards.clevernet.sk/d/Hg9R6uVnk/heat-islands?orgId=1
- **Dashboard comparing locations by climate conditions**, available at https://dashboards.clevernet.sk/d/QKo7ckG4z/temperature?orgId=1
- **Microclimate monitoring dashboard**, available at https://dashboards.clevernet.sk/d/5SaxJA47z/micro-climate?orgId=1&tag=clevernet

These dashboards allowed for the long-term data analysis and subsequent evaluation developed in this report. They also allowed to investigate technical issues, i.e. HW reliability or connectivity limits of the sensor network. for which a special internal dashboard was created:

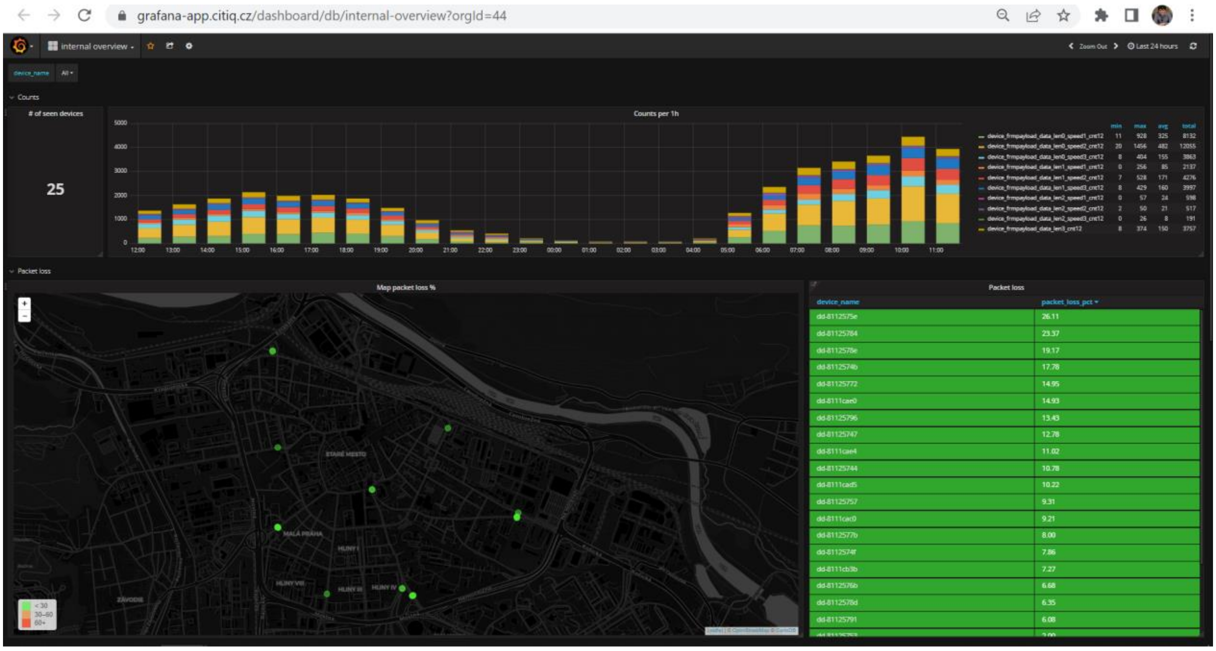
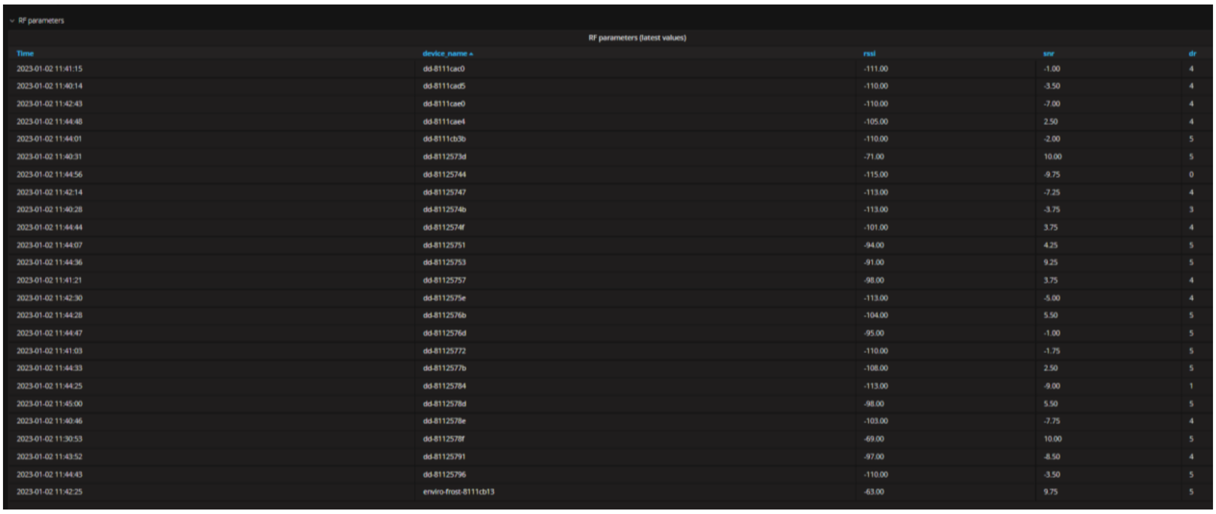


Figure 29: Internal dashboard for monitoring radio network parameters

Monitored radio network parameters

- Data packet loss (packet loss)
- radio signal strength (rssi)
- radio noise (snr)



RF parameters

RF parameters (latest values)

Time	device_name	rssi	snr	dr
2023-01-02 11:41:15	dd-8111cac0	-111.00	-1.00	4
2023-01-02 11:40:14	dd-8111cad5	-110.00	-3.50	4
2023-01-02 11:42:43	dd-8111cae0	-110.00	-7.00	4
2023-01-02 11:44:48	dd-8111cae4	-105.00	2.50	4
2023-01-02 11:44:01	dd-8111cb3b	-110.00	-2.00	5
2023-01-02 11:40:31	dd-8112573d	-71.00	10.00	5
2023-01-02 11:44:56	dd-81125744	-115.00	-9.75	0
2023-01-02 11:42:14	dd-81125747	-113.00	-7.25	4
2023-01-02 11:40:28	dd-8112574b	-113.00	-3.75	3
2023-01-02 11:44:44	dd-8112574f	-101.00	3.75	4
2023-01-02 11:44:07	dd-81125751	-94.00	4.25	5
2023-01-02 11:44:36	dd-81125753	-91.00	9.25	5
2023-01-02 11:41:21	dd-81125757	-98.00	3.75	4
2023-01-02 11:42:30	dd-8112575e	-113.00	-5.00	4
2023-01-02 11:44:28	dd-8112576b	-104.00	5.50	5
2023-01-02 11:44:47	dd-8112576d	-95.00	-1.00	5
2023-01-02 11:41:03	dd-81125772	-110.00	-1.75	5
2023-01-02 11:44:33	dd-8112577b	-108.00	2.50	5
2023-01-02 11:44:25	dd-81125784	-113.00	-9.00	1
2023-01-02 11:45:00	dd-8112578d	-98.00	5.50	5
2023-01-02 11:40:46	dd-8112578e	-103.00	-7.75	4
2023-01-02 11:30:53	dd-8112578f	-69.00	10.00	5
2023-01-02 11:43:52	dd-81125791	-97.00	-8.50	4
2023-01-02 11:44:43	dd-81125796	-110.00	-3.50	5
2023-01-02 11:42:25	enviro-frost-8111cb13	-63.00	9.75	5

Figure 30: Tabular overview of sensors and their connectivity parameters

Conclusions on the limits of the LoRawan network

The connectivity of LoRawan is sufficient for the purpose of an urban sensor network; its limits are in the range of the network, where the reliability (packet loss) decreases with the distance of the sensor from the LoRa gateway and the level of noise (snr) caused by local systems (mainly security systems). The Bratislavská site, which is approximately 1km away from the LoRa gateway and which is close to a petrol station with a radio communication alarm system, showed more significant levels of packet loss and in some periods the outages were significant. Thus, when deploying sensor networks in dense urban areas (city centres), it is necessary to reinforce the network at more distant locations from the central LoRa gateway to overcome high noise levels. This is especially true for sensors that are installed below the surface, such as traffic magnetometers or surface and subsurface temperature sensors, whose signal strength is affected by both material obstructions (e.g. asphalt layer) and low signal values in rain, where the water film is a damping element for the radio signal.

Annex 5 Evaluation of the benefits and use of sensor networks for transport purposes

This annex was prepared by transport experts from the University of Žilina. It is a more detailed description of the use of traffic data for more efficient traffic management and modelling.

Project intent

The key motivation for the project was that while in the commercial sphere the investment in sensor networks is judged by the return on investment (e.g. in the case of deployment of industrial sensor networks, the so-called IoT), in public services the economics is not the primary objective; the focus is on certainty (regularity and reliability, e.g. of public transport connections, supply of free parking capacity, safety), on quality of the service (e.g. health care) and its availability (non-discrimination).

The overall aim of the project was to create a catalogue of use cases of sensor networks and their appropriate application in public sector investments.

The project included the implementation of a "living laboratory", which was implemented within the city of Žilina. Sensors used to monitor traffic intensity were applied at all important entrances and exits from the city centre. The location of the sensors can be seen in Figure 1 (note that the size of the green circle depends on the size of the traffic intensity at the monitored locations).

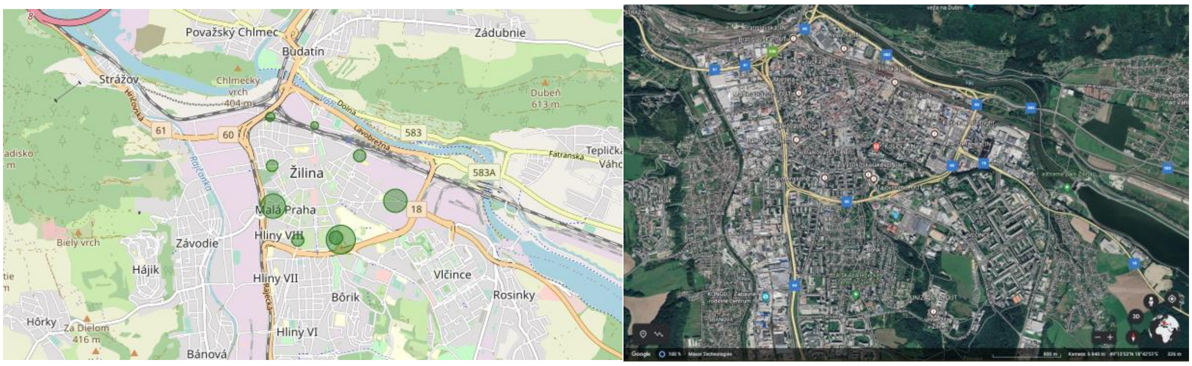


Figure 31: Sensor network in Žilina

Sensor network

The advantage of the sensor network is to monitor the current state of the road network. In case of an emergency situation (e.g. construction works on a given road, traffic accident, congestion, etc.) there is a high probability of redirecting traffic to nearby roads. The sensor network detects a change in either the intensity or the reduced speed of vehicles, which evokes that a situation is occurring at a given location that may lead to, for example, the formation of traffic jams. In this case, the given information would be sent to the available information panels, variable message signs, which would lead to informing other road users about the given situation, the overall delay in a given direction, or an alternative route.

Example of use in Žilina

The sensor network is designed to detect all vehicles entering or leaving the city centre of Žilina. A total of nine entrances are covered, the specific location is shown in Figure 31.

From the existing road network layout, the road network can be "divided" into two groups:

- Two-lane, directionally divided road (streets Bratislavská, Kysucká, 1 Mája, Komenského, and Tajovského - double lane to the intersection, under SHELL petrol station)
- Four-lane, directionally divided road with two lanes in one direction (ul. Hálkova, ul. Vysokoškolákov and ul. Kosická/Predmestská with a turn into the one-way road Štefánikova)

In the case of a two-lane directionally divided road, there was no problem in terms of the number of sensors and their location. In the case of a four-lane directionally divided road (Hálkova Street, Vysokoškolákov Street and Predmestská Street) it was necessary to install a sensor on each lane separately (two lanes towards the city centre, two lanes from the city centre). A total of 26 sensors are installed to monitor the traffic intensity at the given locations. The placement of the sensors in the roadway structure is preferably located at pedestrian crossing points.

Sending data from the sensors to the cloud is via the existing mobile network (see sensor specification). Traffic volume data is sent at 5-minute intervals, then processed and analysed. The data is publicly available (link: https://dashboards.clevernet.sk/?orgId=1, but here the data is aggregated to a minimum interval of 15 min.), allowing anyone to view or download the data and subsequently work with it.

The data recorded by the sensors in Žilina are as follows (the recorded data are software defined, e.g. it is possible to define up to 13 vehicle categories, but the amount of data is limited by the LoRa network properties):

- **vehicle type** (depending on length):
    - short - passenger vehicles, "cars",
    - medium - "van",
    - long - "trucks",
    - uncategorised - "not categorised".
- **vehicle speed**, classification into speed categories:
    - <30 km/h,
    - 30-60 km/h,
    - >60 km/h.

The website allows to view the on-line evaluation. The evaluations are given in real numbers but also in graphical form. A "filter" is available at the top which allows to make a selection:

- either a specific site or all sites at once "all",
- the available data for entering the city "IN", or for exiting the city "OUT",
- vehicle category,
- speed category,
- time group (from a group size of 15 min. to one day).

A tab is available in the upper right corner which allows to view older data (archive).

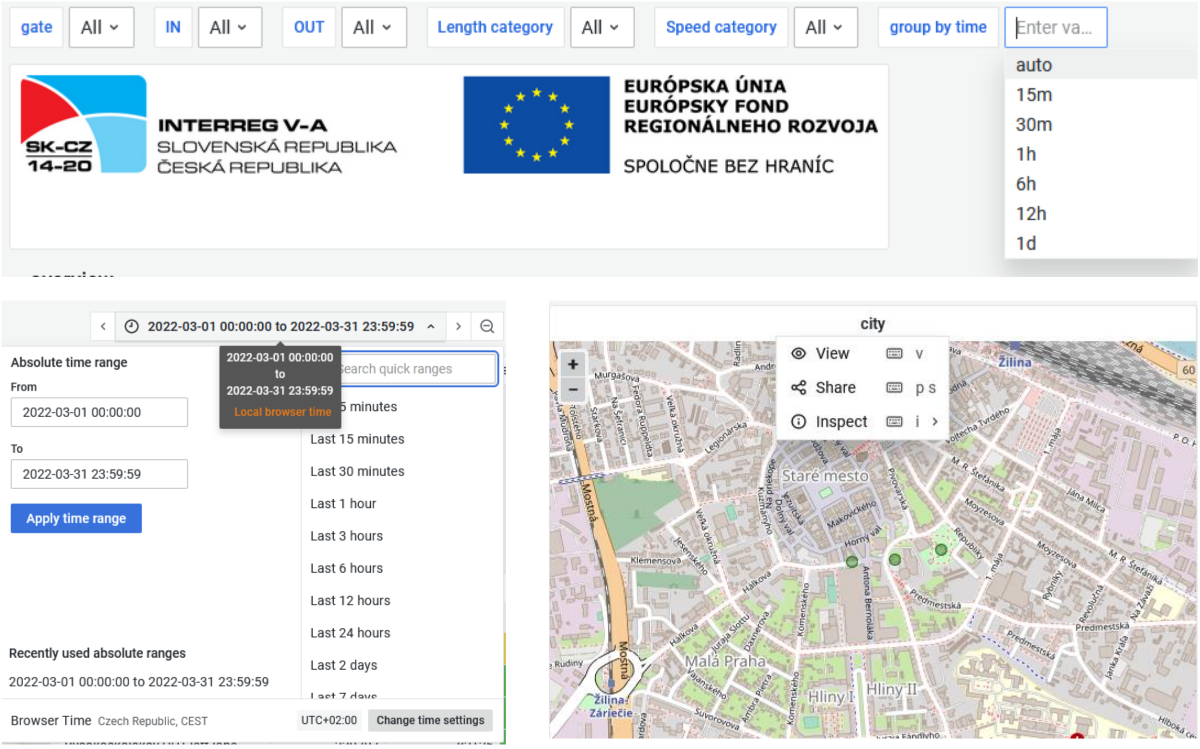


Figure 32: Example of filtering, displaying and exporting data

The deployed network thus represents the first IoT traffic geofencing of a city centre in Central Europe, which enables long-term and continuous monitoring of how the city breathes in terms of traffic. It is thus possible to analyse and study phenomena occurring in the city and to find solutions to traffic problems, e.g. in the field of urban logistics, traffic safety, static traffic or the environment.

The section below shows a map of the city of Žilina, on which the locations of the sensors are shown with a list of names. Following are the evaluated data for specific vehicle groups, speed categories with numerical as well as graphical representation. The graph shows time on the x-axis and the number of vehicles on the y-axis, with the y-axis in positive and negative. The positive value represents us the entrance to the city and the negative value shows the exit of the city.

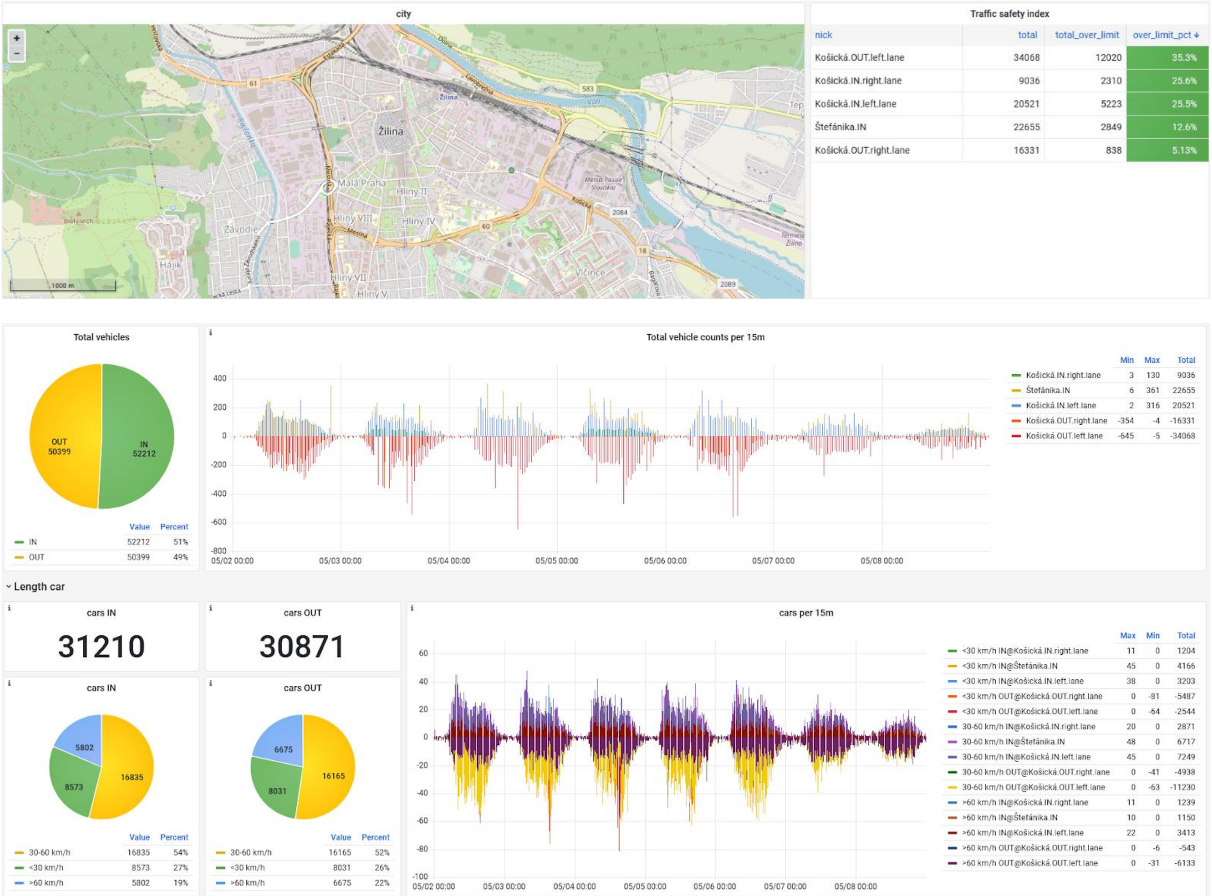


Figure 33: Example of an online traffic data system

To the right of the map view there is the **Traffic safety index** (for a given data filter setting), which indicates the rate at which vehicles exceed 60 km/h.

The sensor network was deployed in the summer of 2021 and traffic data is therefore available for a sufficiently long period of time. A basic insight into traffic in the city centre gives us an indication of the number of vehicles entering and leaving the city centre. The graph below shows the number of vehicles entering the area per month over a one-year period. Thus, 16 million vehicles enter the city centre annually, the month with the lowest number of vehicles entering the city centre was February 2021 (1.173 million vehicles/month), the peak was recorded in May 2022 (1.474 million vehicles/month)

Typically 300-335k vehicles enter the centre per week, 44 thousand vehicles per day. The recorded maximum was 64k. vehicles/day (Maundy Thursday). These numbers are equivalent to 4 entrances by a resident of the centre per day.

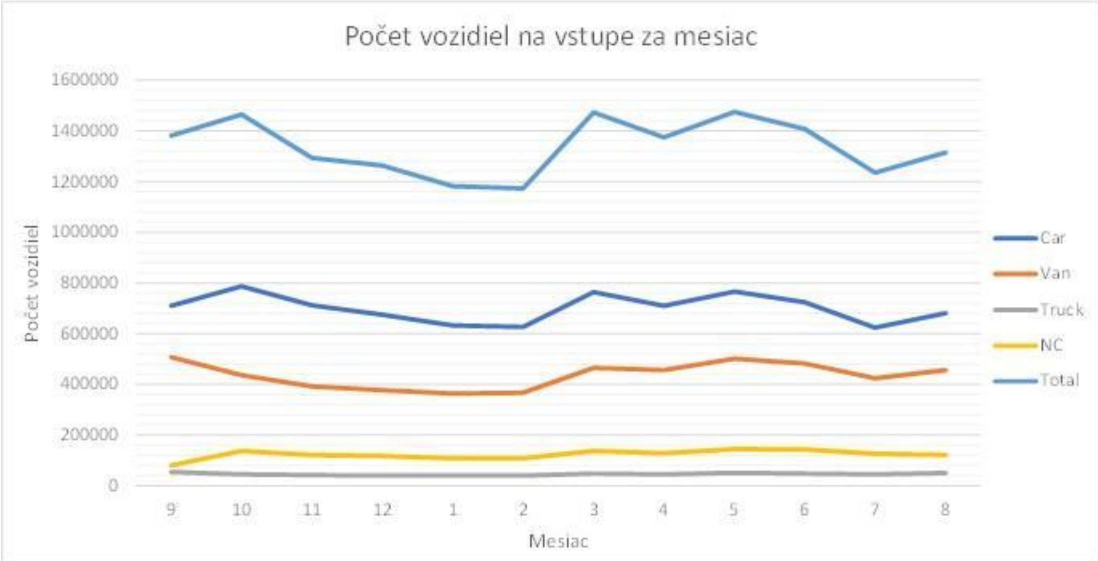


Figure 34: Number of vehicles entering the centre per month

It goes without saying that traffic at the various entrances to the centre varies not only in number but also in character. Thus, we have entrances with a relevant share of the catchment area source/target traffic (Hálkova, Košická, Kysucká) and also entrances with typical inner-city traffic (Komenského, Vysokoškolákov, Tajovského).

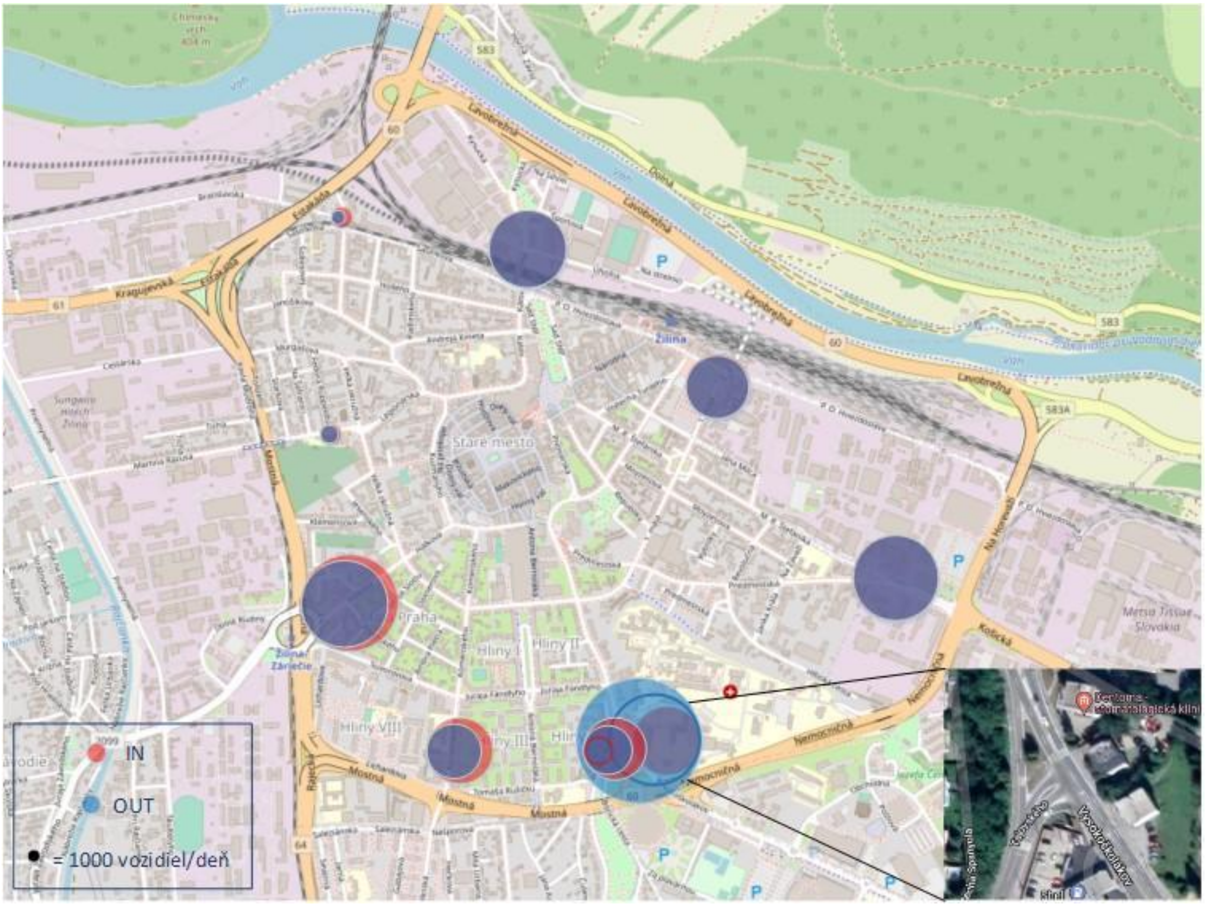


Figure 35: Comparison of the number of vehicles entering and exiting the zone

Note on the display at the Tajovského and Vysokoškolákov entrance: the intersection at Shell petrol station has a specific shape with the Tajovského/Vysokoškolákov turning lane, whereby such a traffic stream enters and immediately exits the centre. Thus, the circle represents all sensor data, the circle represents the subtracted flow at the Tajovského/Vysokoškolákov turn-off.

The data allows us to visualize the breathing of traffic in the city centre during the day. Below is an example for a weekday. It can be seen, for example, that the rush hour at the entrance to the zone is on Hálkova Street in the morning and in the afternoon. The traffic at the entrance on Košická Street behaves similarly, but Kysucká Street has a more significant peak only in the morning, about an hour earlier.

WD	Tajovskéh	Komenske	Kysucká	Hálkova	Košická	Vysokošk	1.mája	Bratislavsl	Rázusa	Tajovskéh	Komenske	Kysucká	Hálkova	Košická	Vysokošk	1.mája	Bratislavsl	Rázusa
23:00	10,2	41,4	47,4	46	40,4	40,4	29,6	13,8	4,8	-25,2	-17,2	-33,2	-42,6	-33,2	-59,8	-26,4	-6,2	-6,2
0:00	7,2	17,2	15,6	34,2	10,8	13,2	20,8	7,4	3,4	-5,6	-23,6	-19,6	-36	-19,6	-20	-21,4	-2,8	-3,4
1:00	2,6	13,8	11	15,6	17,2	11,8	6,6	5,4	2	-6	-6,8	-13,6	-10,6	-13,6	-11	-8,6	-4	-3,6
2:00	3,8	9,4	12,6	10	6	6,4	5	8,6	0	-6,8	-1,6	-11	-13,4	-11	-5	-5,6	-2	-2,4
3:00	1,2	9,4	9,8	8	13,6	5,2	12	6,2	1,6	-3,8	-6,6	-15	-10,2	-15	-12,4	-9,4	-4,8	-6,8
4:00	4,6	11,6	23,8	24,2	23,4	21	17	9,6	1,4	-6,8	-9,4	-21,4	-25,6	-21,4	-26,8	-16,8	-1,8	0
5:00	28,4	65	145	101,8	172,2	58,4	80,4	46,2	28,2	-23,4	-38,4	-88,8	-95,4	-88,8	-95,4	-103,4	-41,4	-30,8
6:00	103,2	173	451,8	373,2	488,8	197,6	213,4	129,4	80	-87,2	-95,2	-279,2	-237,8	-279,2	-163,2	-236,8	-58,2	-57,2
7:00	194,4	482,8	600,4	802	769	445	393,6	113,2	226,8	-268,6	-391,2	-361,4	-405,4	-361,4	-377,8	-349,6	-55	-95,8
8:00	159,6	524,2	638	850,8	691,6	568,8	438,8	279,2	240	-348	-221,8	-357,2	-599,2	-357,2	-635,6	-381	-107,2	-115,8
9:00	169,4	448,2	528,6	830	638,2	460,4	344	217,2	184,6	-287,8	-295,8	-461,6	-561,8	-461,6	-505,8	-346,6	-54,2	-113,6
10:00	172,8	357,4	500,2	678,6	551	466,8	431,8	97,2	163,8	-260,4	-369,8	-462,6	-464,8	-462,6	-642,8	-402,4	-150,8	-115,4
11:00	88,2	535,8	377,4	577,2	557,8	465,8	401,4	196	162,2	-315,6	-502,4	-482,2	-692,8	-482,2	-535,6	-443,6	-103	-77,4
12:00	164,2	435,6	431	638,4	594,4	365,8	370,6	138,4	182,8	-297,2	-278,2	-483,2	-632,8	-483,2	-531,8	-402,8	-96	-162
13:00	273,8	374,8	464,6	638,8	453,6	448	425,8	272,2	167,4	-356	-361,6	-505,4	-660,8	-505,4	-462	-417,2	-142,2	-143,4
14:00	142,4	401,8	401,2	753,8	548	466,4	439,4	197,8	175,6	-394,2	-362,8	-476,6	-583	-476,6	-883,8	-422	-101	-148,8
15:00	173,6	533,4	345,2	796,8	602,4	490,4	453,2	356	156,6	-433,6	-571,6	-753,6	-520,6	-753,6	-639,2	-421	-68	-203,8
16:00	152,6	537,4	370,4	782	470,8	405,2	457,4	179,2	170,6	-511,4	-289	-546,8	-657,8	-546,8	-556,8	-424	-116,6	-186,8
17:00	111,4	377,8	342	535,2	441,6	340,6	383,2	157,2	109,6	-383,2	-540,4	-493,6	-696	-493,6	-564,2	-354,6	-129,4	-148,4
18:00	108	275,2	310,4	318,4	380,6	330,6	317,6	97,2	74,8	-289,2	-319	-408,6	-519,4	-408,6	-423	-293	-43,6	-79,2
19:00	227	246,8	276,6	396,4	295,6	239,8	203	76	60	-256,6	-193	-266,6	-357,2	-266,6	-348,2	-219,2	-45,2	-55
20:00	89	201,6	188,2	255	216,8	222	186	77,4	51,6	-143,2	-121,6	-250	-291,8	-250	-346,4	-181,8	-32	-24,8
21:00	50	141,8	155,2	143,4	170	139,4	142,6	39,2	36,6	-82,8	-174,2	-160,8	-198,2	-160,8	-217,4	-132,4	-27,4	-56,4
22:00	44,6	75	116	80,6	88,4	81,4	99,2	57,8	13,8	-60,4	-75,8	-133,4	-139,2	-133,4	-119,4	-117,2	-25	-28,6
	2482,2	6290,4	6762,4	9690,4	8242,2	6290,4	5872,4	2777,8	2298,2	-4853	-5267	-7085,4	-8452,4	-7085,4	-8183,4	-5736,8	-1417,8	-1865,6

WD	Tajovskéh	Komenske	Kysucká	Hálkova	Košická	Vysokošk	1.mája	Bratislavsl	Rázusa
23:00	-15	24,2	14,2	3,4	7,2	-19,4	3,2	7,6	-1,4
0:00	1,6	-6,4	-4	-1,8	-8,8	-6,8	-0,6	4,6	0
1:00	-3,4	7	-2,6	5	3,6	0,8	-2	1,4	-1,6
2:00	-3	7,8	1,6	-3,4	-5	1,4	-0,6	6,6	-2,4
3:00	-2,6	2,8	-5,2	-2,2	-1,4	-7,2	2,6	1,4	-5,2
4:00	-2,2	2,2	2,4	-1,4	2	-5,8	0,2	7,8	1,4
5:00	5	26,6	56,2	6,4	83,4	-37	-23	4,8	-2,6
6:00	16	77,8	172,6	135,4	209,6	34,4	-23,4	71,2	22,8
7:00	-74,2	91,6	239	396,6	407,6	67,2	44	58,2	131
8:00	-188,4	302,4	280,8	251,6	334,4	-66,8	57,8	172	124,2
9:00	-118,4	152,4	67	268,2	176,6	-45,4	-2,6	163	71
10:00	-87,6	-12,4	37,6	213,8	88,4	-176	29,4	-53,6	48,4
11:00	-227,4	33,4	-104,8	-115,6	75,6	-69,8	-42,2	93	84,8
12:00	-133	157,4	-52,2	5,6	111,2	-166	-32,2	42,4	20,8
13:00	-82,2	13,2	-40,8	-22	-51,8	-14	8,6	130	24
14:00	-251,8	39	-75,4	170,8	71,4	-417,4	17,4	96,8	26,8
15:00	-260	-38,2	-408,4	276,2	-151,2	-148,8	32,2	288	-47,2
16:00	-358,8	248,4	-176,4	124,2	-76	-151,6	33,4	62,6	-16,2
17:00	-271,8	-162,6	-151,6	-160,8	-52	-223,6	28,6	27,8	-38,8
18:00	-181,2	-43,8	-98,2	-201	-28	-92,4	24,6	53,6	-4,4
19:00	-29,6	53,8	10	39,2	29	-108,4	-16,2	30,8	5
20:00	-54,2	80	-61,8	-36,8	-33,2	-124,4	4,2	45,4	26,8
21:00	-32,8	-32,4	-5,6	-54,8	9,2	-78	10,2	11,8	-19,8
22:00	-15,8	-0,8	-17,4	-58,6	-45	-38	-18	32,8	-14,8
	-2370,8	1023,4	-323	1238	1156,8	-1893	135,6	1360	432,6

Figure 36: Breathing of traffic in the centre of Žilina during the working day (top, red = IN/IN, green = OUT/OUT) and the difference in the number of vehicles (IN-OUT)

Application in traffic management and planning

Traffic models

The sustainability of tools for monitoring, analysing, and predicting traffic conditions can be ensured by actively linking the data trace to the traffic model. Mesoscopic models are most commonly used for strategic transport solutions. The path from source to destination is the basic modelling unit. For the correct adjustment of the traffic flow through the road infrastructure, periodic calibration of the traffic situation on the road infrastructure is indispensable. The sensor network of a city offers itself as an ideal data collection system with almost immediate use in a local traffic model. The following example shows the traffic model of the city of Žilina. The model is defined on the basis of a series of traffic surveys (profile, directional, cordon, etc.). Data from traffic sensors increase the efficiency of use. Thus, the model administrator can determine the traffic variations in a given profile over several time periods, days.

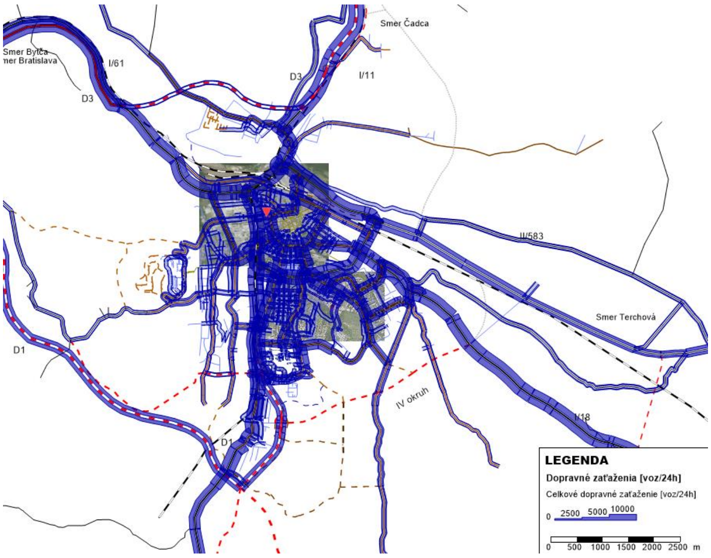


Figure 37: Traffic model of Žilina

The sensor localization can be converted into a traffic model according to the selected geo-referencing system. The points (sensor locations) are then assigned to individual road network sections. One sensor can be defined for each profile and direction. Data from the sensor network can be imported, for example, via a text file. In a higher version of the traffic model, such data can be retrieved online. An example of the defined sensors on the network is shown in the following figure.

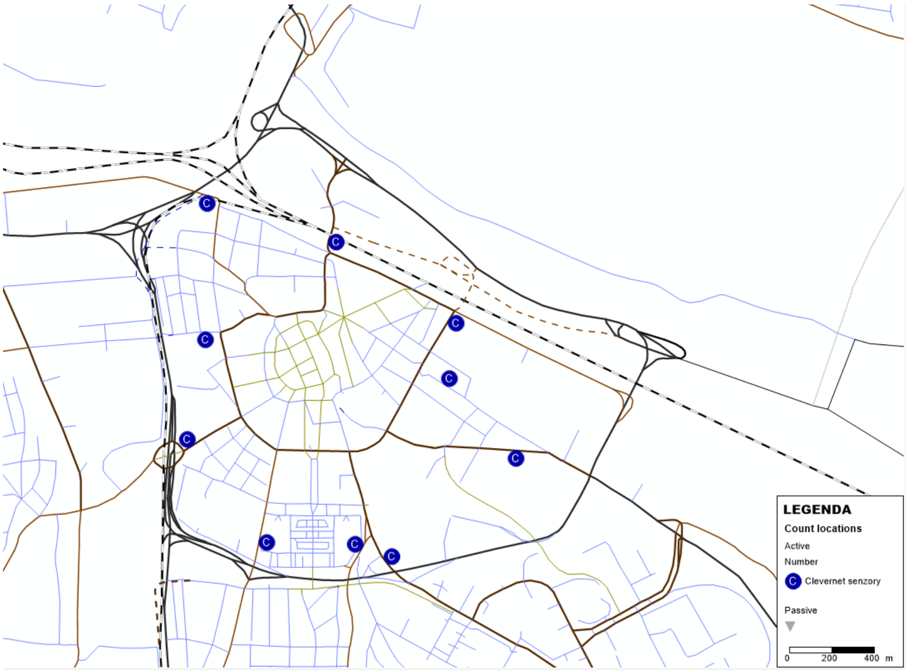


Figure 38: Defining sensors in the model

By combining the user interface menu of software functions and the analysis of sensor network data, several traffic load scenarios can be processed and evaluated. This allows the model builder to validate a scenario with load in special traffic conditions such as public holidays, Friday, weekend traffic or a cultural event. The following figure shows a comparison of the model traffic load and the actual sensor data.

Figure 39: Example of data retrieval from the Clevernet project database

Another useful application is to monitor traffic on a profile and with a model to determine the direction of traffic flows in the area. The user can verify not only the intensity on the profile, but also the source and destination of the vehicles.

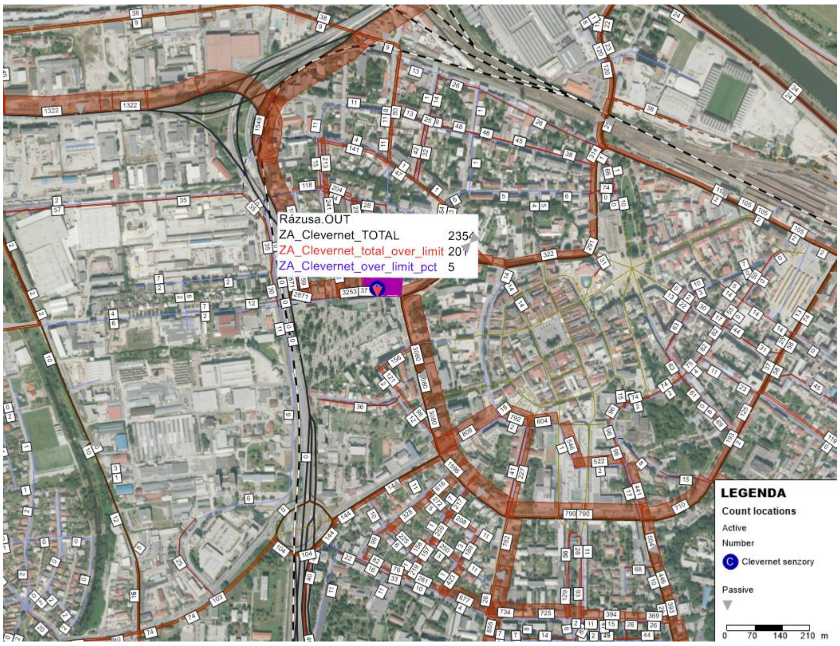


Figure 40: Combination of traffic model data and actual traffic data

Microscopic models

Microscopic models focus on a specific vehicle, its behaviour (driver behaviour), characteristics and interactions with other vehicles in the traffic flow. The development of a microscopic model requires a high quality of the underlying detailed spatial data, e.g. a detailed geometric layout of the area to be considered (number and width of lanes, positions of traffic signs, dimensions of vehicles, their weight, maximum speed or acceleration values). The microscopic model calculates time delays, vehicle speeds, length of columns, infrastructure throughput, etc. The main purpose of microscopic models is as an assessment tool:

- **Detailed engineering design of infrastructure elements** (e.g. intersections in a part of a city, track layout of a railway station),
- **Detailed traffic-organisational measures in a specific location** (e.g. traffic control and routing at an intersection).

The detailed sensor output includes the time track of the crossing, the speed and the vehicle category. Using a programming package, it is possible to identify the traffic condition on the profile and then evaluate or, via a decision algorithm, change traffic control elements such as traffic lights, variable message signs, etc.

Figure 41: Microsimulation model of a traffic node with the possibility of defining local detectors

Constraints on the traffic network

Another example of the use of the sensor network in Žilina is the measurable demonstration of a change in the traffic organisation due to the current ongoing construction works on the reconstruction of the railway junction in Žilina, including the railway station. During the construction, the railway underpass, which is used for crossing from Kysucká Street to P.O.Hviezdoslava Street, was closed.

The reconstruction project of the Žilina railway junction is planned for a long time, therefore it was necessary to assess the change of traffic in the centre of Žilina after the closure of the section on Kysucká. The following figure is the result of the simulation of the traffic model with the assumed closure of Kysucká Street without additional measures (note: the project also foresees the construction of the connection of 1. Mája and Ľavobrežná Streets over the railway, but due to the property settlement it was not possible to implement it before the start of the project).

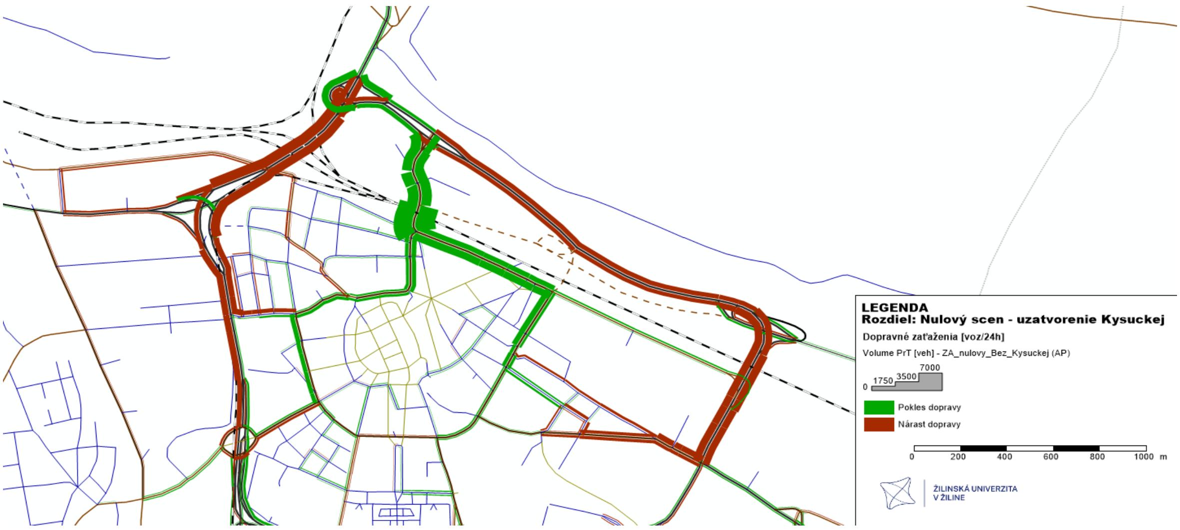


Figure 42: Model of traffic load changes in the centre of Žilina after the start of the railway junction reconstruction

The real situation before this change is illustrated by the following graph, which shows the numbers of vehicles typically passing through Kysucká Street to the city centre (IN) and from the city centre (OUT). On weekdays 7000 vehicles per day arrive via this route, while almost 6000 vehicles per day leave the centre. Weekend traffic is typically down 40% from weekdays, and on a holiday during the week (e.g., 11/17/2022) the drop in traffic on this stretch is up to 55%. The difference between directions is approximately 20%.

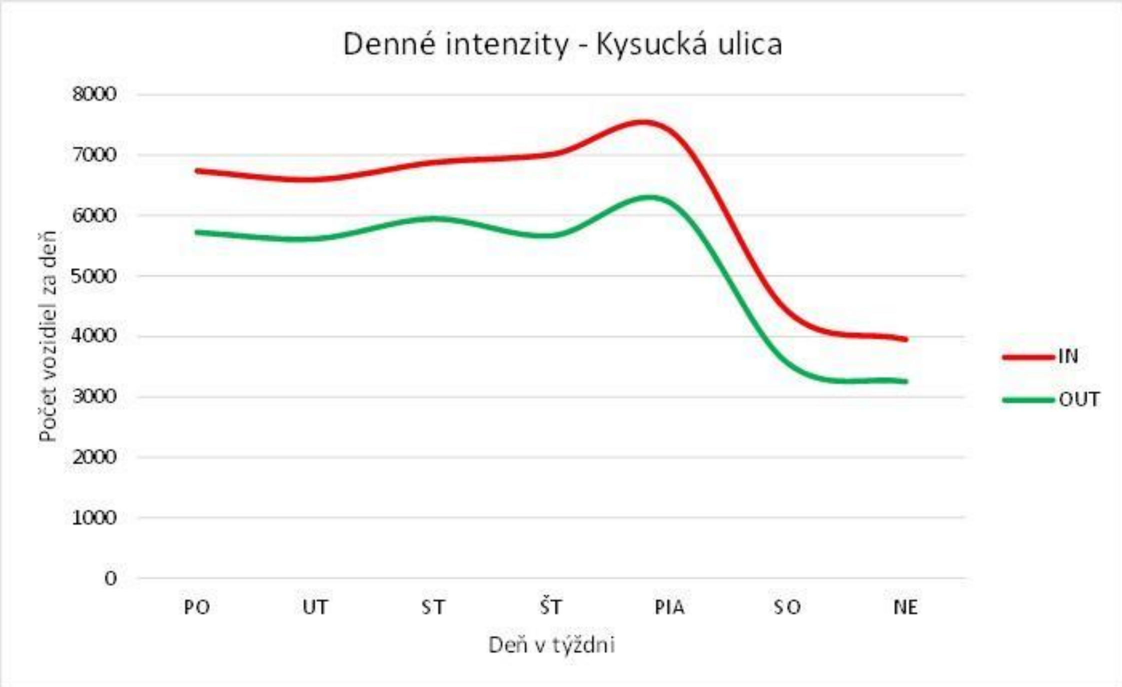
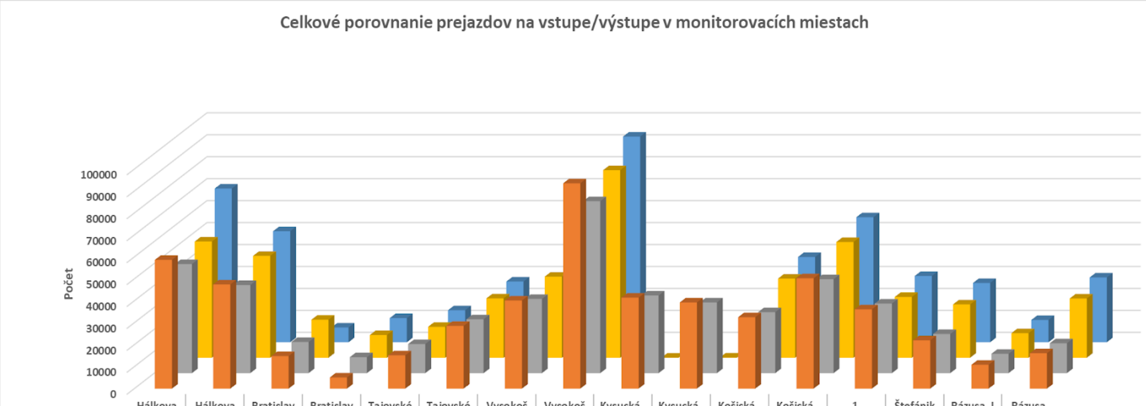


Figure 43: Overall comparison of the number of trips (entering/exiting the city centre) at the traffic monitoring locations

During a typical week, 43k people come through this road to the city centre and only 36k use the road for the exit. The closure of the section at Kysucká street (where the traffic sensors were located and thus recorded zero traffic intensity) must have increased the intensity at other monitored entrances to the city centre of Žilina.

The following graphs show the increase or decrease in the number of records at individual monitoring entrances in the period of two weeks before and two weeks after the closed underpass (closure of the underpass happened at midnight from 20.11.2022 to 21.11.2022).

The total number of recorded crossings at all entrances and exits are shown in Figure 44.

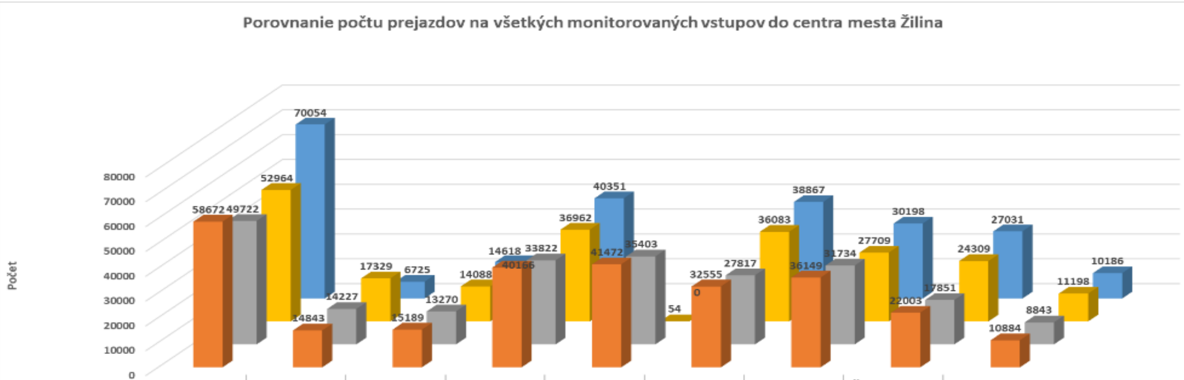


	Hálkova_IN	Hálkova_OUT	Bratislavská_IN	Bratislavská_OUT	Tajovského_IN	Tajovského_OUT	Vysokoškolákov_IN	Vysokoškolákov_OUT	Kysucká_IN	Kysucká_OUT	Košická_IN	Košická_OUT	1. mája_IN	Štefániková_IN	Rázusa_IN	Rázusa_OUT
7.-13.11.2022	58672	47482	14843	5103	15189	28599	40166	93549	41472	39293	32555	50284	36149	22003	10884	16122
14.-20.11. 2022	49722	40165	14227	7295	13270	24569	33822	78357	35403	32253	27817	42822	31734	17851	8843	13641
21.-27.11. 2022	52964	46425	17329	10329	14088	27056	36962	85459	54	93	36083	52754	27709	24309	11198	27007
28.11.-4.12. 2022	70054	50602	6725	11010	14618	27684	40351	93722	0	0	38867	56979	30198	27031	10186	29533

Figure 44: Overall comparison of the number of trips (entering/exiting the city centre) at the traffic monitoring locations

For a simpler representation of the traffic situation, depending on the closure of the underpass, the overall graph was divided into a graph showing the number of crossings at all monitored entrances to the Žilina city centre, Figure 45, and a graph showing the number of crossings at all monitored exits from the Žilina city centre, Figure 46.

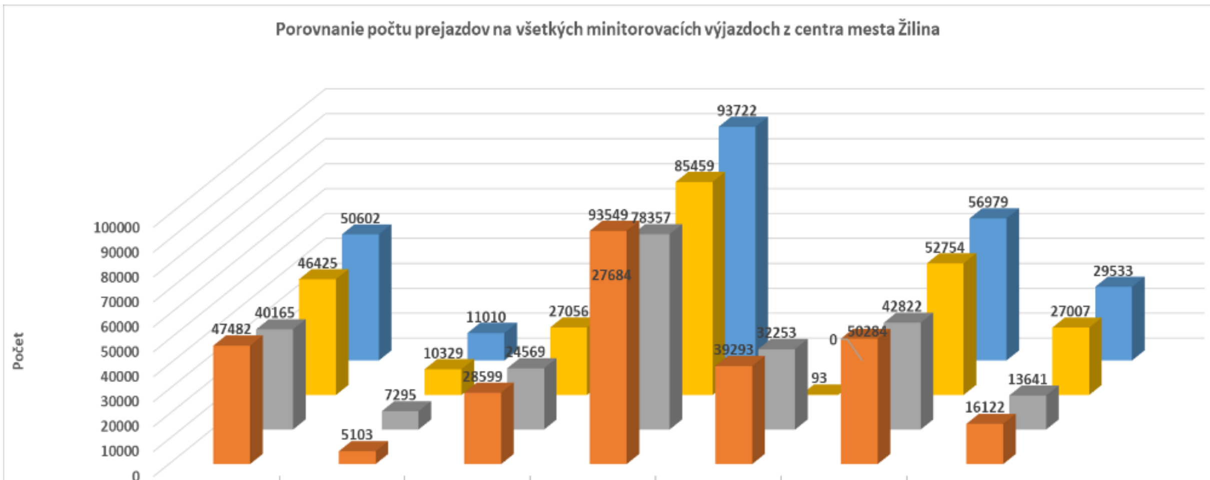
The data shows a change in the distribution of traffic in the city, with the highest increase on Košická Street (8266 vehicles). Vehicles coming from Ľavobrežna Street preferred a new route, namely via Košická Street.



	Hálkova_IN	Bratislavská_IN	Tajovského_IN	Vysokoškolákov_IN	Kysucká_IN	Košická_IN	1. mája_IN	Štefániková_IN	Rázusa_IN
7.-13.11.2022	58672	14843	15189	40166	41472	32555	36149	22003	10884
14.-20.11. 2022	49722	14227	13270	33822	35403	27817	31734	17851	8843
21.-27.11. 2022	52964	17329	14088	36962	54	36083	27709	24309	11198
28.11.-4.12. 2022	70054	6725	14618	40351	0	38867	30198	27031	10186

Figure 45: Comparison of the number of crossings at all monitored entrances to Žilina city centre

A significant change in the number of cars at the city exit was detected on Martina Rázusa Street (Figure 46). The total difference between the period before and after the closure of the underpass on Kysucká Street is 13366 vehicles heading outwards in the city of Žilina.



	Hálkova_OUT	Bratislavská_OUT	Tajovského_OUT	Vysokoškolákov_OUT	Kysucká_OUT	Košická_OUT	Rázusa_OUT
7.-13.11.2022	47482	5103	28599	93549	39293	50284	16122
14.-20.11. 2022	40165	7295	24569	78357	32253	42822	13641
21.-27.11. 2022	46425	10329	27056	85459	93	52754	27007
28.11.-4.12. 2022	50602	11010	27684	93722	0	56979	29533

Figure 46: Comparison of the number of crossings at all monitored exits from Žilina city centre

A closer view of the flow shift after the closure of Kysucká Street is shown in the following figure.

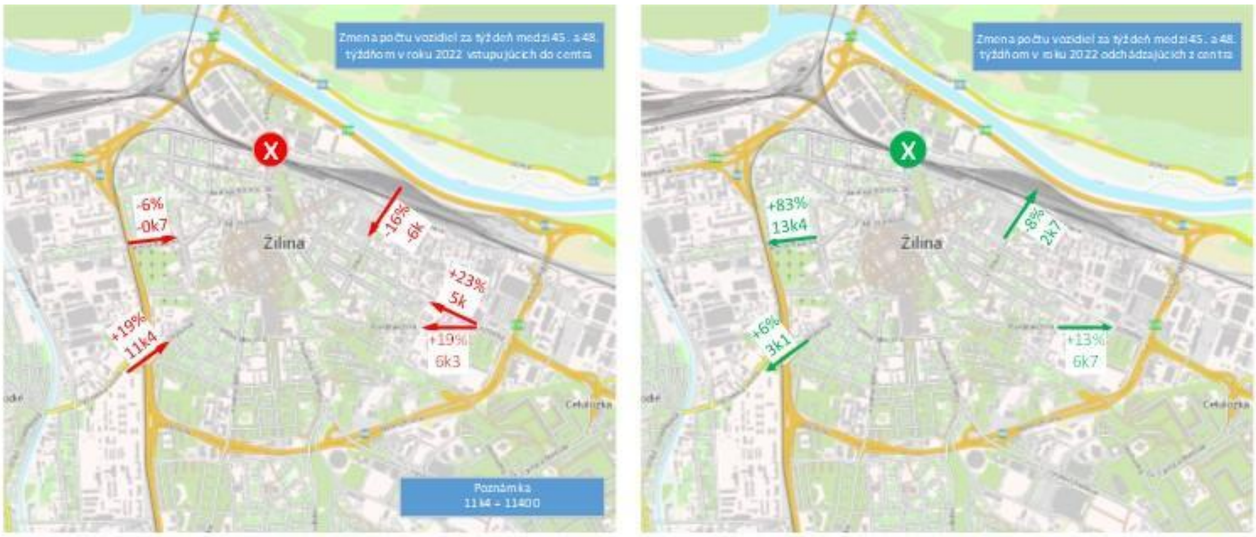


Figure 47: Change in the number of vehicles per week between week 45 and week 48 in 2022 entering and exiting the centre

The change was evaluated for the period of week 45 and week 48 because week 46 was a holiday (11/17) and the first week after the closure of Kysucká street was a transition week, drivers were getting used to the changes in traffic organization.

As expected, Hálkova (via Mostná) and Košická (via Ľavobrežná) became the replacement for the entrance gate to the centre on Kysucká street. In the opposite direction - from the centre - Martina Rázusa Street was also added, where there was a significant increase in all categories, but in the TRUCK category there was an increase of more than 6 times (mainly due to the rerouting of public transport vehicles via this street).

Strategic traffic modelling in the wider area

The strategic traffic models differ mainly in the level of detail. Compared to the urban models, the study area is larger. Traffic zones are generally bounded by the cadastral boundaries of municipalities or urban districts of towns. The principle of traffic monitoring by a sensor network has its application in the analysis of rerouting, especially of transit traffic in an area where multiple routes can be used. Continuous recording of intensities on profiles in a wider area can be used to describe the attractiveness of alternative routes under specific conditions (increased intensity, weather, construction closures, etc.). The data can be applied to predictive traffic models, either short or long term. The following figure shows an example of a traffic model for the Žilina municipality. In the model, sensors are defined that currently contain a sample of data from a weekly traffic record. This data is essential in the calibration of the traffic model.

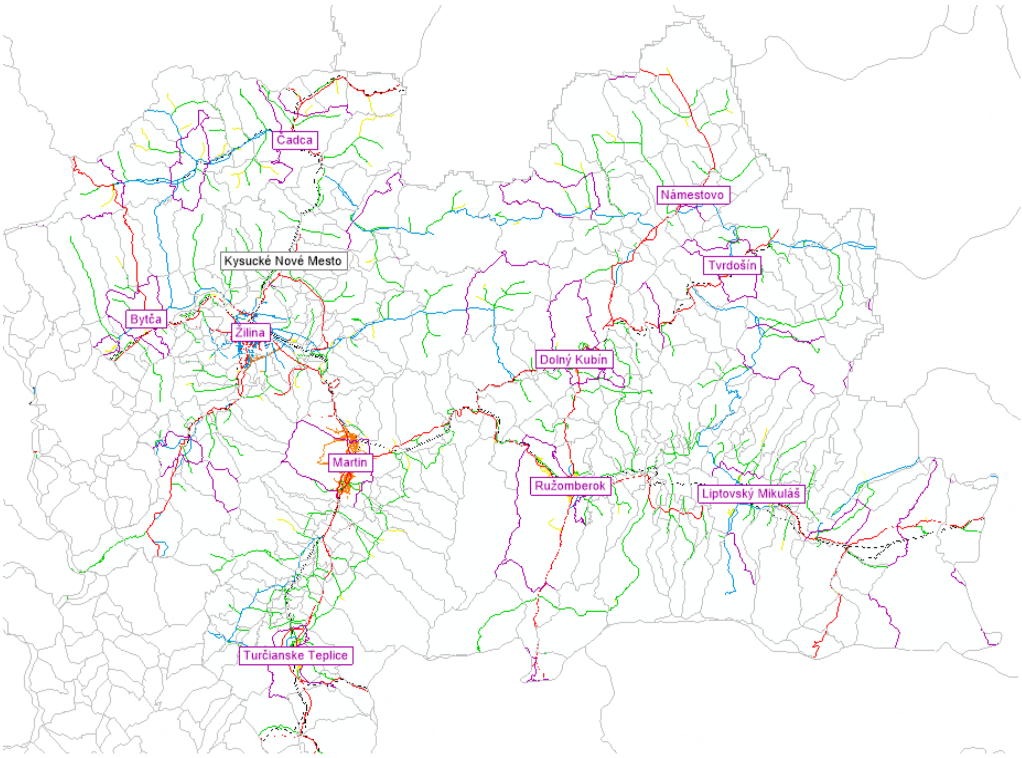


Figure 48: Transport model of Žilina region

Other use cases

Road safety

Sensors are placed at pedestrian crossing points. Therefore, we know at what speed vehicles are travelling in the pedestrian crossing section (direction of travel IN/OUT). The data thus serve as a basis for the development of measures to increase the safety of pedestrians crossing the roads, or to design traffic calming features.

Speeding statistics show that approximately one fifth of all vehicles exceed 60km/h. This is most pronounced in the VAN category.

Smer	>60 km/h	Car >60 km/h	Van >60 km/h	Truck >60 km/h
IN	20,5%	17,8%	32,4%	18,3%
OUT	19,4%	13,1%	39,6%	22,6%

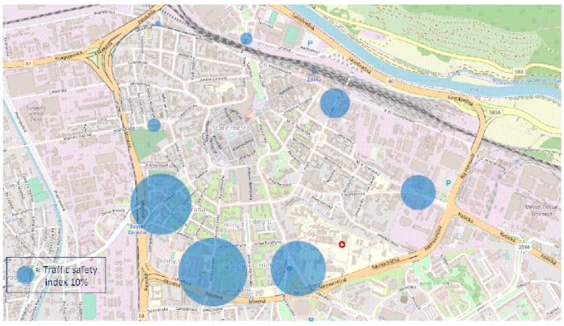


Figure 49: Speeding statistics

The most serious speeding occurs on the following profiles: Hálkova OUT left lane, Komenského IN and Vysokoškolákov IN right lane.

The most serious location is Hálkova Street, which is defined by the nature of the traffic (higher proportion of out-of-town traffic) and the geometry of the site.

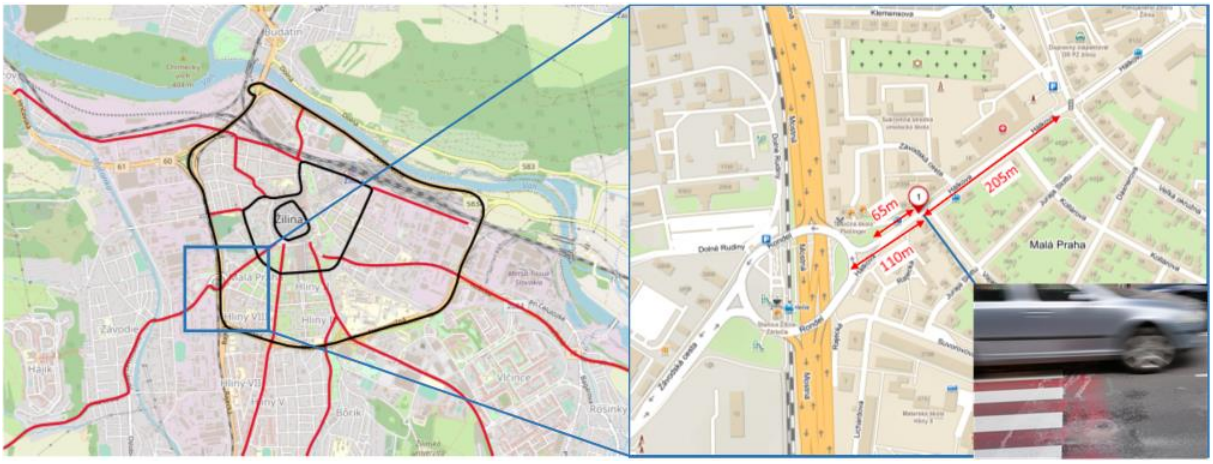


Figure 50: Location of Hálkova Street and detail of the street with distances from the pedestrian crossing (sensor locations)

The data analysis showed that there is a strong dependency between traffic volume and speeding. The following figure shows an example from the days April 8, 2022 - April 10, 2022 (Friday to Sunday).

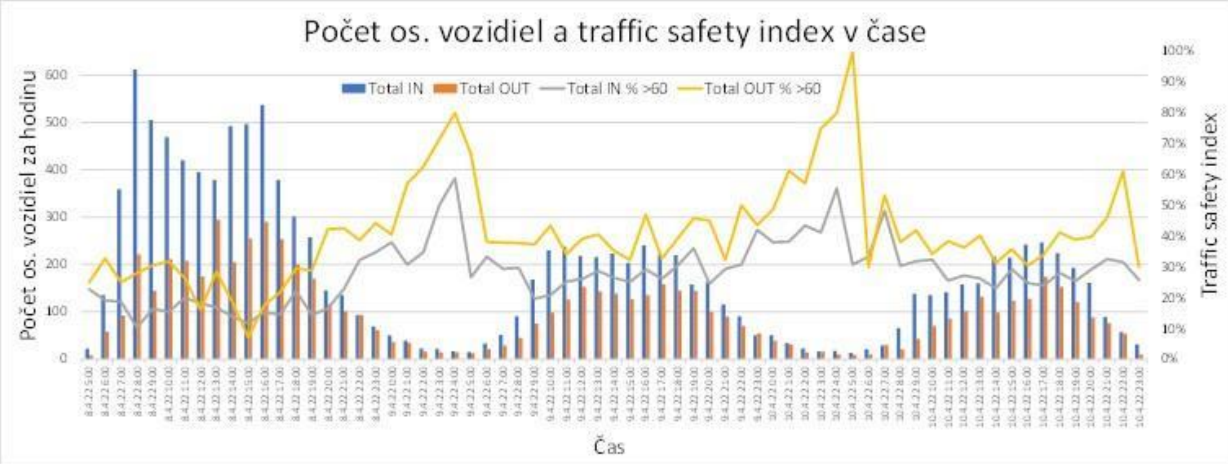


Figure 51: Intensity and traffic safety index for the period 8.4. 2022 - 10.4. 2022

It also shows that not only the difference between traffic directions but also between lanes is relevant. The following graph for the same case - place and time - shows the dependency between the intensity (number of vehicles per hour) and the 60 km/h speeding rate (traffic safety index).

There is a fundamental difference between the lanes, which results both from the geometry of the section and from the behaviour of the drivers. In the direction to the centre, the geometry and sight distance factors prevail, whereas in the direction from the centre, the human factor prevails - the left lane is used by drivers intending to proceed to the Rondel roundabout, while the right lane is used by unexperienced drivers, right-turning drivers and public transport vehicles.

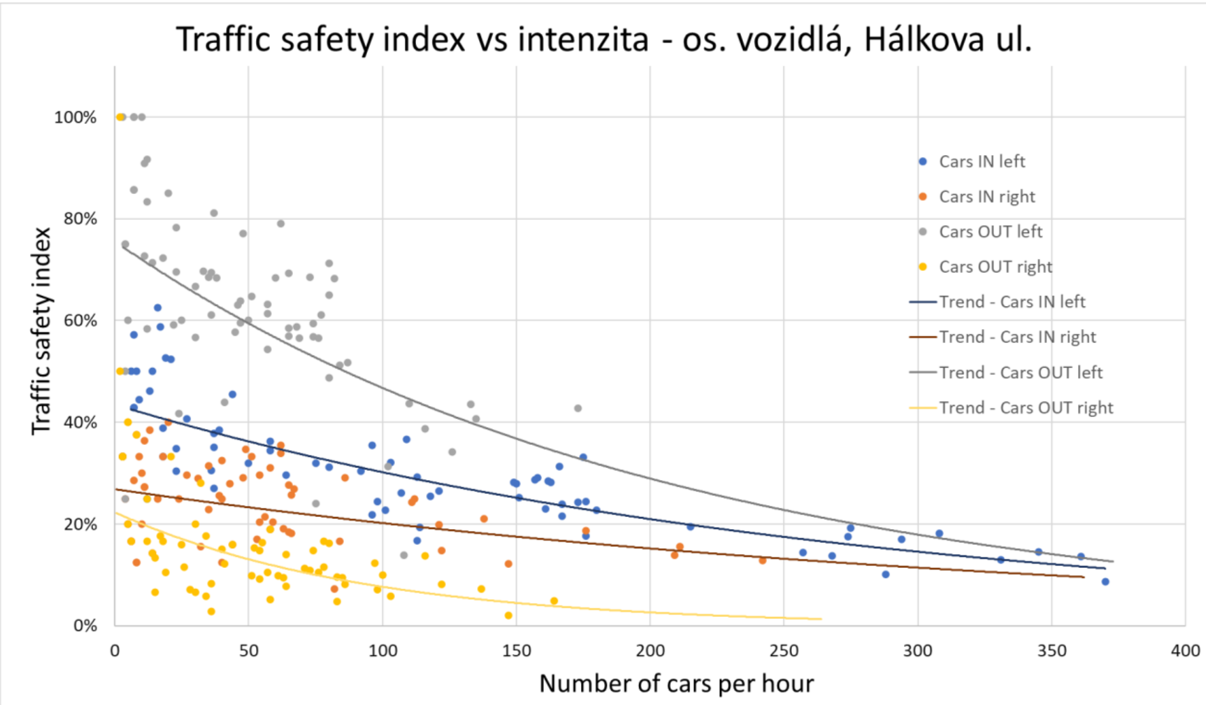


Figure 52: Example of speeding-intensity relationship for Hálkova Street

Interaction of traffic and environment

The sensor network for continuous sensing of traffic conditions on the road network can be applied to other monitoring devices. Monitoring the emission load in the intracity provides a picture of the air quality. By combining measurement records with traffic characteristics, it is possible to determine the dependence of air quality status on changes in traffic intensity.

Weather equally influences traffic. As part of the sensor network, frost sensors are also deployed to sense surface and subsurface (-6 and -30 cm) temperatures and include a salinity sensor. Temperature sensors also include selected traffic sensors and measure subsurface temperature (experience shows that close to surface temperature).

Based on the data from these sensors, icing can be detected, and this information can be used to improve safety on roads and pavements.

In terms of road and pavement management, it can be used by administrators to control the performance of chemical winter maintenance.

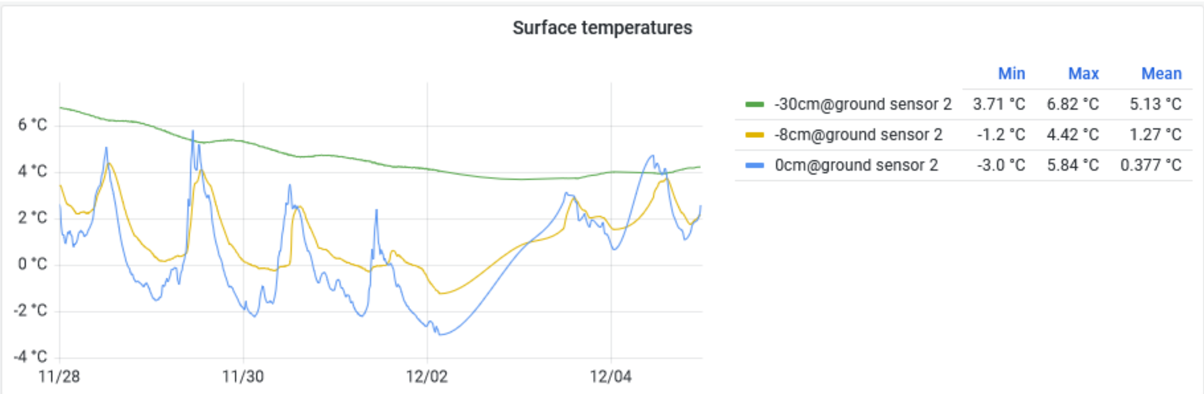


Figure 53: Example of the temperature waveform on the frost sensor at the UNIZA campus

Road works

The case of a section closure on an urban radial that has substantially affected traffic in the city centre was described above.

Traffic can also be significantly affected by work on or near the road. An example is the situation on Štefánikova Street in the 2nd half of 2022.

In a positive way, this has affected vehicle speeds, with a relevant reduction in speeding.

Also, the closure of the railway underpass on Kysucká Street is reflected in this graph, then at the turn of the year we can see the impact of Christmas and therefore reduced activity.

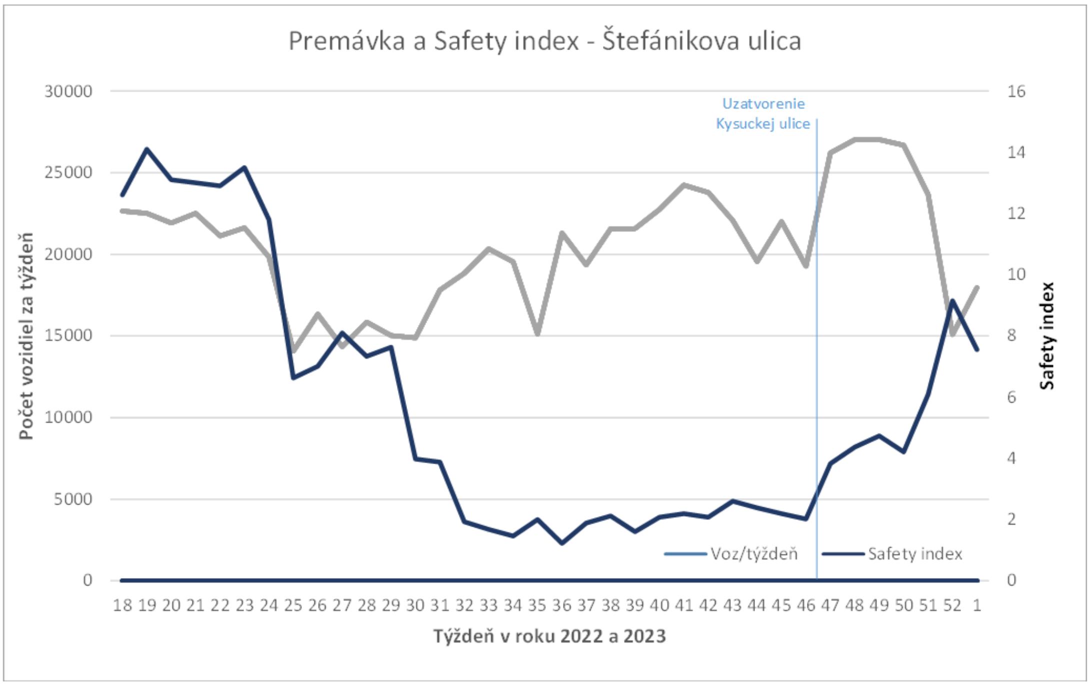


Figure 54: Weekly intensities and safety index on Štefánikova Street in the second half of 2022

Static traffic – parking

The number of vehicles entering and leaving the centre naturally varies over time - during the time of day. An example is given in the following figure for weekday (WD) and weekend (WE).

The graph shows the different daily patterns of the number of vehicles entering and leaving the centre.

Obviously, some vehicles will stay in the zone in question, and parking options for these vehicles need to be addressed. In Žilina there is a defined system of on-street parking and there are also two shopping centres with high-capacity underground parking in the centre.

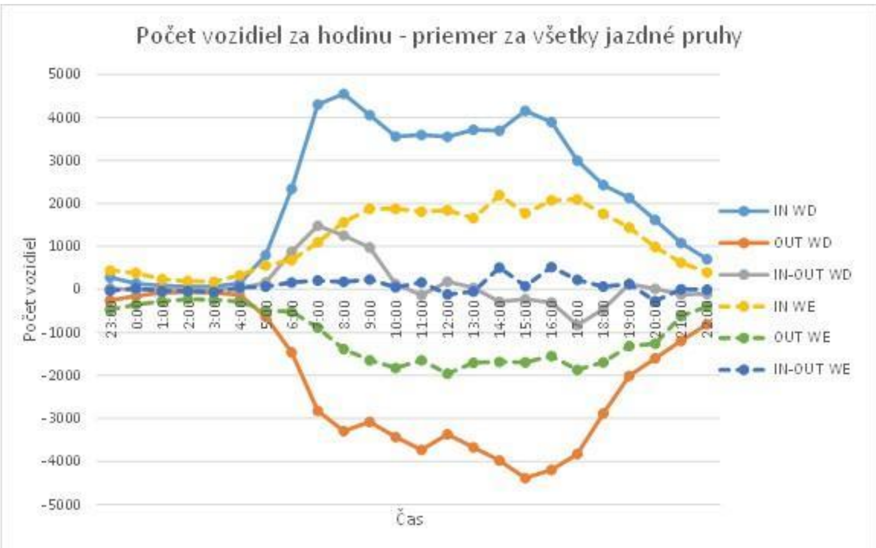


Figure 55: Traffic intensities over time during the day (for the week 30.5.-5.6.2022, WD - weekday, WE - weekend)

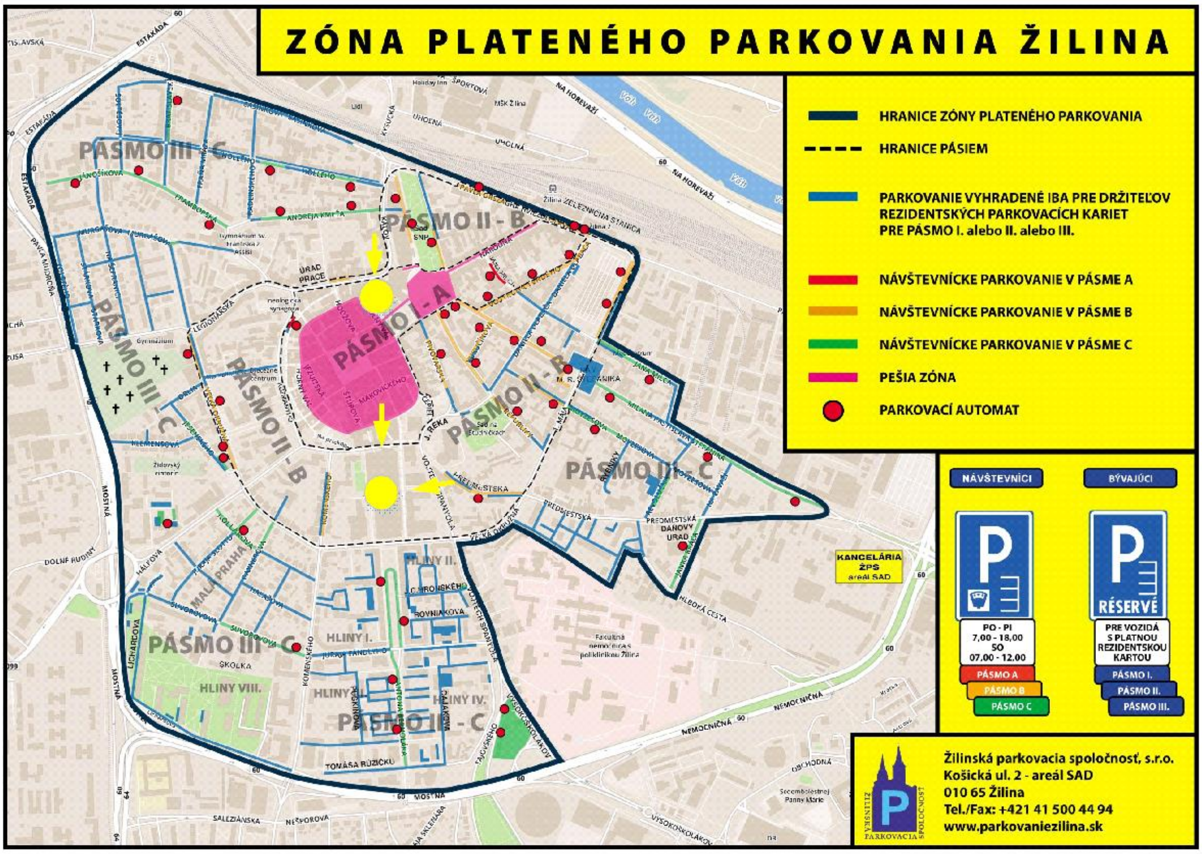


Figure 56: Zones of paid parking in Žilina with parking houses marked (based on the source www.parkovaniezilina.sk)

Other options

Other possible uses of the data from the deployed sensor network are the study of induced traffic, warming of public space by traffic, development support, phenomena affecting traffic (fusion with other data).

Bibliography

[1] ZELEŇ A ZÁSTAVBA V ŽILINE V KONTEXTE ZMENY KLÍMY, http://zelenza.worldfrom.space/

[2] Sangiorgio, V., Fiorito, F. & Santamouris, M. Development of a holistic urban heat island evaluation methodology. *Sci Rep* 10, 17913 (2020). available on: https://doi.org/10.1038/s41598-020-75018-4

[3] Hove, Bert & Steeneveld, Gert-Jan & Jacobs, Cor & Heusinkveld, Bert & Elbers, Jan & Moors, Eddy & Holtslag, Bert. (2011). Exploring the Urban Heat Island Intensity of Dutch Cities. Plant Journal - PLANT J. available on: https://edepot.wur.nl/171621

[4] Oke, T. & Canada,. (2006). Initial guidance to obtain representative meteorological observations at urban sites, available on: https://www.researchgate.net/publication/265347633_Initial_guidance_to_obtain_representative_meteorological_observations_at_urban_sites.

[5] Wong, Man & Nichol, Janet & Ng, Edward & Guilbert, Eric & Kwok, Kai & To, Pui & Wang, Jingzhi. (2010). GIS techniques for mapping urban ventilation, using frontal area index and least cost path analysis. International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences - ISPRS Archives. 38. available on: https://www.researchgate.net/publication/229037744_GIS_techniques_for_mapping_urban_ventilation_using_frontal_area_index_and_least_cost_path_analysis

[6] Urban Heat Island Mitigation Strategy Toolkit [online]. available on: https://www.cip-icu.ca/Files/Resources/STUDIO2-RYERSON-UHI-TOOLKIT-FINAL-REPORT.aspx

[7] ŻEBROWSKI, Marcin. *COOL IT DOWN - Tackling urban heat island effect in Singapore* [online]. 2021. available on: https://www.slideshare.net/Marcinebrowski2/cool-it-down-tackling-urban-heat-island-effect-in-singapore-marcin-ebrowski-master-thesis. Master Thesis.

[8] *The UHI Risk Index for Austria: Introduction* [online]. available on: https://eocs.blob.core.windows.net/adapt/FactsheetUHIRiskIndex.pdf

[9] Nakata, Camila M., and Léa C. L. de Souza. "VERIFICATION OF THE INFLUENCE OF URBAN GEOMETRY ON THE NOCTURNAL HEAT ISLAND INTENSITY." *Journal of Urban and Environmental Engineering*, vol. 7, no. 2, 2013, pp. 286–92. *JSTOR*, http://www.jstor.org/stable/26189199 Accessed 4 Jan. 2023.

[10] SANTAMOURIS, Matheos. *Natural Ventilation in Urban Areas* [online]. 2004, 10. available on: https://www.aivc.org/sites/default/files/members_area/medias/pdf/VIP/VIP03.Urban%20Ventilation.pdf

[11] JOHANSSON, Lars. *Modelling near ground wind speed in urban environments using high-resolution digital surface models and statistical methods* [online]. 2012 [cit. 2023-01-04]. available on: http://lup.lub.lu.se/student-papers/record/2534839. Diplomová práce. Lund University, Department of Physical Geography and Ecosystems Science.

[12] BEZRUKOVA, D.N, E. STULOV a D.M. KHALILI. *A Model for Road Icing Forecast and Control* [online]. 2009. available on: https://www.semanticscholar.org/paper/A-Model-for-Road-Icing-Forecast-and-Control-Bezrukova-Stulov/cd175ec8db77b1059cd607676760956143ee3200