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# ENHANCING STRATEGIC TRANSPORT MODELLING THROUGH MULTI-SOURCE DATA INTEGRATION: A CASE STUDY OF THE ŽILINA SUMP

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## Abstract

Strategic transport models have become an indispensable tool for sustainable urban planning, extending their necessity even to medium-sized cities. This paper presents the comprehensive overhaul of the macroscopic transport model for the city of Žilina, Slovakia, as part of the development of its Sustainable Urban Mobility Plan (SUMP). The model, now in its fourth generation (2025), features a significantly refined demand model, achieved through an innovative multi-source data integration philosophy. The core of the update involved moving beyond traditional survey methods to incorporate a wide array of Big Data and administrative data sources. The methodology describes the practical application and synthesis of: anonymized Mobile Network Data (MND), real-time traffic data from TomTom, national census data from the Statistical Office of the Slovak Republic, and inputs from a local sensor network. A key contribution of the APVV project was the processing and analysis of a set of 842 nationwide Origin-Destination (O-D) matrices provided by the mobile network operator, Orange. From this national dataset, statistically significant data were subsequently selected and interpreted, which powerfully reflect Žilina's role as a major road and rail hub and its complex regional travel patterns. Furthermore, the paper addresses the significant shift in mobility caused by increased teleworking. Findings from the Horizon Europe project "WinWin4WorkLife" were used to adjust trip generation, reflecting new work-life dynamics. The result is a functionally-enhanced model that provides the analytical foundation for the current SUMP. The article details the model's concept, the data fusion process, and its use in defining Key Performance Indicators (KPIs). As a case study, it demonstrates a replicable approach that enables cities to build more accurate and adaptive transport models to address current mobility challenges.

*Keywords: SUMP, traffic data, model, telework*

## 1 Introduction

Effective transport planning is crucial for ensuring long-term sustainable solutions in urban environments. It enables the creation of solutions that are not only functional but also environmentally and socially responsible, thereby contributing to an improved quality of life in cities. The city of Žilina is a major transport hub in northwestern Slovakia, where important road corridors, including the D1 and D3 motorways, converge, generating intense transit and destination traffic. This location has historically placed a significant burden on the city center and adjacent roads. At the same time, the city is home to the modernized Žilina railway junction, which is one of the largest transport investments in Slovakia and is fundamentally changing the dynamics of mobility in the region. To manage these challenges, an update of the city's key strategic transport document, the Transport Master Plan of the City of Žilina, is essential.

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For clarity, this update is being developed in the form of a new Sustainable Urban Mobility Plan (SUMP), which unifies these strategic efforts. The SUMP serves as the fundamental framework for the planned development of the city’s transport infrastructure and spatial layout, aiming to conceptually address all modes of transport. The update process builds upon the previous SUMP from 2016 and utilizes a wide range of data, such as demographic data, traffic engineering surveys, and urban planning forecasts [1]. The entire process is logically divided into three stages. The first stage focuses on data collection and analysis, as well as working with the transport model. The second involves drafting the development strategy and assessing its environmental impacts, while the third stage delivers the final proposal of specific measures. The foundation for all phases is the acquisition of high-quality, relevant data, which is crucial for the creation and calibration of the city’s strategic transport model. This model, continuously developed at the University of Žilina since 2007, is capable of predicting future traffic development and simulating the impacts of proposed changes.


**Figure 1** a) Locality of Žilina in Slovakia; b) Žilina transport model

The master plan update also closely integrates the principles of the Sustainable Urban Mobility Plan (SUMP), which emphasizes meeting the mobility needs of residents and businesses while simultaneously improving their quality of life [2]. The SUMP promotes an integrated approach, public participation, and continuous evaluation of implemented measures. The final proposal, optimized for the 2030 and 2045 time horizons, will thus represent a comprehensive plan that considers not only the technical but also the environmental and social aspects of mobility development in Žilina. The analysis also drew upon data and insights from the Transport Plan of the Žilina Region, which was likewise prepared by the University of Žilina (UNIZA) [3]. Both models adopted the model structuring principles and the database from the National Model of the Slovak Republic [4]. This article delves into the creation process of this strategic document, with an emphasis on the use of complex data analysis, including big data, and its integration with long-term research projects conducted at the University of Žilina.
Therefore, this paper focuses primarily on presenting a novel methodological approach for integrating complementary data sources to parameterize distribution functions and to assess transport quality based on network speed. The scientific contribution is demonstrated by applying this framework to determine the significance of various economic sectors on the prevalence of remote work, utilizing an ordered logit model.

## 2 Multi-source data

To create a robust and accurate strategic document, the use of diverse and up-to-date data sources is crucial. While the original transport model was built on the foundation of traditional surveys from 2010–2015, its comprehensive update in 2025 relied on a combination of proven methods and new technologies.

## 2.1 Traditional data collection methods

In this study, we combined two classical approaches, a profile survey and a mobility survey, with continuous monitoring via a heterogeneous sensor network in the city of Žilina [5]. The profile survey collected respondents' demographic and socio-economic data (age, gender, economic activity) as well as their motivations for choosing particular transport modes. The field-based mobility survey then complemented these insights by tracking nearly 1,000 individual trips in the most densely populated districts, recording trip origin and destination, purpose, mode of transport and duration; approximately 85% of participants were economically active. Proven methods remained fundamental for understanding residents' behavior. A supplementary online mobility survey was conducted with a sample of 476 respondents, providing a detailed map of travel preferences and motivations. This dataset was further enriched by key demographic and spatial information from the 2021 Population and Housing Census, which precisely defined transport relationships between city districts. These traditional sources offered invaluable insight into the sociological dimension of mobility. The core innovative data source was a network of 56 heterogeneous sensors deployed across main roads, secondary streets, intersections and cycle paths. Each device continuously recorded traffic volumes and speeds of motor vehicles, cyclists' flows, lane-by-lane occupancy and peak-period load factors. Automated monitoring of public transport operations was conducted in other surveys not described in this article. This extended the scope of conventional field surveys, enabling a detailed and persistent view of traffic dynamics.

**Table 1** Example of evaluated mode choice for first trip

| Mode of transport | Number of trips | Share |
|---|---|---|
| On foot | 76 | 16.0% |
| Bicycle (scooter) | 30 | 6.3% |
| Public transport (MHD) | 134 | 28.2% |
| Car – driver | 211 | 44.3% |
| Car – passenger | 11 | 2.3% |
| Train | 4 | 0.8% |
| Regional bus (SAD) | 10 | 2.1% |

Table 1 presents the modal split for the first observed trip of the study day, illustrating that while Žilina enjoys a relatively high share of cycling, the extremely low car-occupancy rate (only 2.3% of trips with passengers) underscores major inefficiencies in road-space utilization. The primary limitation of the sample is that the survey was completed by only one active member per household, which naturally excluded other groups like children and potentially under-represented individuals from car-free households. Despite these limitations, the sample is considered representative of the target group – economically active residents whose travel behaviour is one of the main focuses of this study. This sample constitutes nearly 1.5% of the population. Furthermore, this analysis serves as a supplement to a more extensive mobility survey conducted in 2015, which included a larger sample of approximately 4, 500 residents (a 5.6% share).

## 2.2 Big data sources

One of the key data sources was data from TomTom, which enables the creation of precise Origin-Destination (OD) matrices [6]. This data, obtained from Floating Car Data (FCD), represents a sample of approximately 20% of all vehicles on the network. Although this may seem like a low sample rate, high statistical accuracy can be achieved by aggregating the data over long periods, such as for all average weekdays during spring and autumn (over 100 days), and combining it with data from sensor networks. Figure 2 illustrates two examples of how this data can be used. The image on the left presents traffic flow patterns in the area in front of the railway station. The analysis revealed that nearly 70% of trips in this area are internal (local) trips, while the remaining 30% constitute through traffic (figure 2, left). This finding is crucial, as a key project outcome is the proposal to create a multimodal space in front of the station with a preference for non-motorized transport, followed by a reorganization of traffic on the parallel Uhoľná Street, where through traffic can be rerouted. Another important network performance indicator was the analysis of travel speeds. The speed analysis included an evaluation of the ratio between the 85$^{th}$ percentile of observed speeds and the posted speed limit for a given road segment. This was followed by an assessment of the Level of Service (LOS), with a particular focus on key urban arterials, such as radials and ring roads (figure 2, right). From the perspective of road authorities, a significant conclusion was that intersections appearing to have sufficient capacity in traditional studies are, in fact, not reaching their limits. This is due to a saturated state in the surrounding area, which prevents a larger volume of traffic from reaching them.

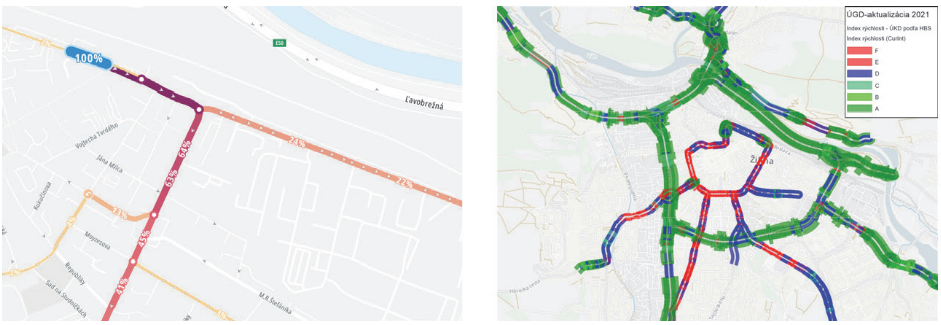


**Figure 2** OD relations from exact road segment (left) and speed LOS evaluation during morning peak (right)

Anonymized mobile data from operators Orange Slovakia and Orange France also represent a significant source, enabling the tracking of spatial movement patterns of SIM cards and, consequently, the population's daily mobility (figure 3) [7]. We procured a database structured into two zonal divisions: one for Slovak districts and another for Orange-defined zones (1, 574 in total). Within the project, this data was tested primarily from the perspective of trip distribution. A key limitation of the data is that it lacks information on transport modes and trip purposes. A total of 842 files were provided, featuring various trip detection criteria (e.g. age groups, SIM card type). Based on this transformed data, scripts were developed to evaluate trip distribution functions according to population and specific locations.
Figure 4 (left and right) depicts a comparison of four theoretical distribution functions (normal, log-normal, gamma, and Weibull) with empirical trip length data, where the quality of fit was evaluated using the coefficient of determination ($R^2$) [8]. These trips were defined through trajectory segmentation, treating any time gap in movement longer than 1 hour as an interruption and the start of a new trip.

The evaluation indicates that while the **log-normal distribution** was the best-fitting model for the nationwide data **(figure 4, left)** with an $R^2$ of 0.820, the **gamma distribution** achieved the highest accuracy for the O-D relations concerning Žilina **(figure 4, right)** with an $R^2$ of 0.897, although the log-normal distribution also showed a comparably high fit ($R^2$ = 0.889). The results, therefore, confirm that the log-normal model is most suitable for the national-level data, whereas the gamma distribution provides the best approximation at the regional level.

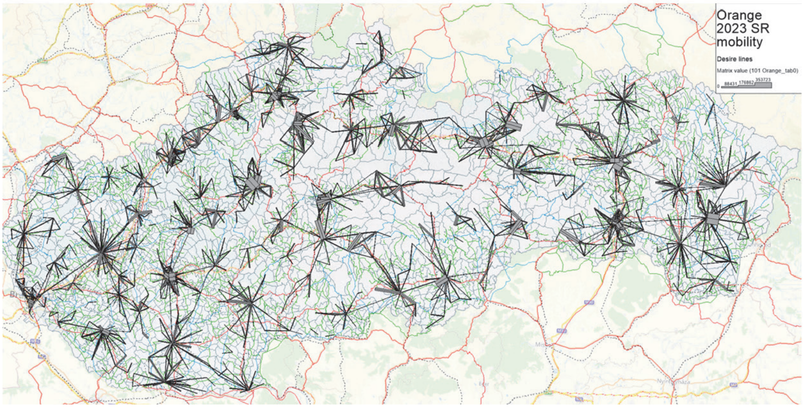


**Figure 3** OD relations for Slovakia based on SIM card movements

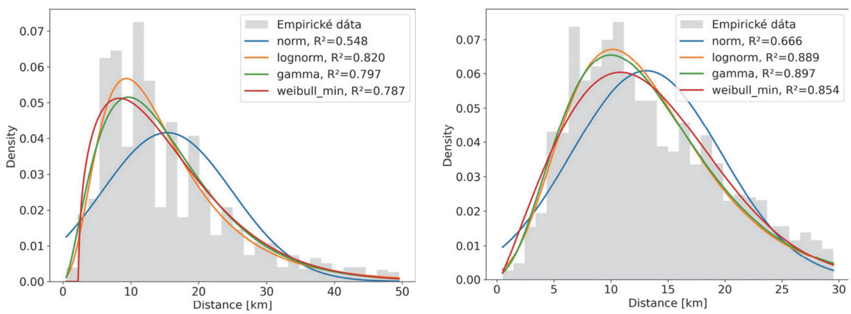


**Figure 4** Comparison of Fitted Distribution Functions for a 1-hour Time Lag: Nationwide Data (left) vs. Žilina O-D Relations (right)

## 3 Telework impact

For the analysis of this phenomenon across Slovakia, the latest data on commuting from the 2021 Population and Housing Census, which was conducted during the pandemic, were used and supplemented with data from the Statistical Office of the Slovak Republic [9, 10]. An ordered logit model was applied to evaluate the share of people working from home, followed by an analysis of the estimated parameters of the utility function. This model is specifically suited for analyzing outcome variables that have a natural, ranked order (e.g. frequency of remote work). Its primary purpose was to test changes in the utility function parameters across several land use development variants. Furthermore, it served to monitor the changing potential for remote work under these scenarios. The results confirm that sectors such as administration and information technology are dominant in the field of remote work.

However, it is crucial to emphasize that the main limitation of the analysis is the data collection period, which took place during the COVID-19 pandemic, potentially skewing the overall results. Figure 5 shows a part of the territory where a sector such as Agriculture is dominant, a fact that clearly points to the influence of the COVID period. For a more accurate assessment of the current and future situation, it is necessary to obtain more detailed data, for example, through a nationwide mobility survey, which is currently lacking in Slovakia. The University of Žilina is addressing this very issue in depth as part of the international Horizon Europe project No. 101095167 WIN-WIN4WorkLife, titled “A win-win strategy for a better work-life balance through smart teleworking for all stakeholders”.

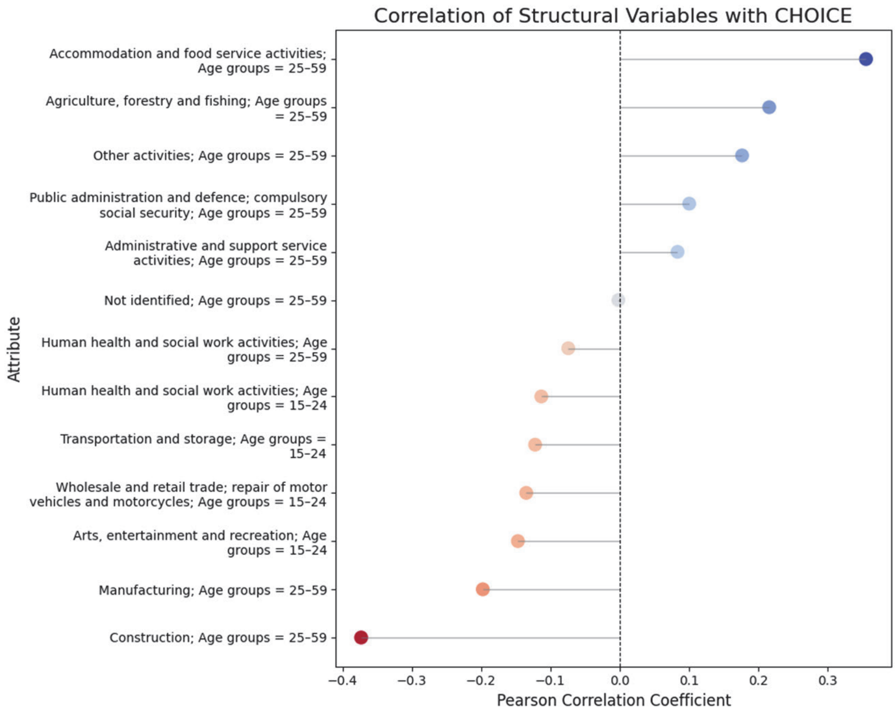


**Figure 5** Example of Corelation of Structural Variables with choice of Telework impact during COVIDfor specific area

Analysis of the parameters according to the classification of economic activities (NACE) revealed that in 2021, the work-from-home alternative was most attractive for sectors such as accommodation and food services. This effect, with a p-value of 0.00895, is statistically highly significant. The positive coefficient does not reflect work in direct contact with customers but is likely driven by administrative and managerial positions within the sector that shifted to the online space. In contrast to the clear effect of accommodation and food services, the effect of the administrative services sector did not have the same statistical strength

## 4 Application

By combining multiple data sources – from traditional mobility surveys and census data to modern “big data” from mobile networks and navigation systems – we were able to gain an adequate picture of how transport actually functions in the city. Detailed analyses revealed not only where and when congestion occurs but also the real travel habits and needs of the people.

Based on these findings, we outlined strategic visions and principles for long-term sustainable mobility. For instance, the data analysis clearly confirmed that many trips are short, which reinforced the vision of a city that prioritizes pedestrian and bicycle transport. The precise identification of congestion locations and their causes led to the principle of strengthening public transport as a viable alternative to the car by enhancing its priority and reliability. Furthermore, uncovering the problems of monofunctional zones and the poor connectivity of new developments created the foundation for promoting mixed-use development, which reduces the need for travel.
Data on traffic flows and speed profiles precisely identified critical points, such as the congested inner ring road and problematic connections to the city center. This allowed us to propose concrete, and even bold, solutions, such as optimizing traffic management or strategically rerouting traffic to free up public space. As the transport model was able to predict future scenarios based on this data, it also led to proactive visions, such as the need to strictly regulate transit freight traffic to prevent the city from experiencing gridlock following the opening of new motorway sections.

## 5 Conclusion

This paper describes the development process of Žilina's updated Transport Master Plan and demonstrates how a multi-source data approach forms the foundation for an effective urban mobility strategy. By combining traditional data collection methods, such as surveys and census information, with advanced "big data" from mobile network operators and traffic-monitoring services, a transport model was created. Furthermore, the inclusion of contemporary factors like the impact of teleworking, analyzed through advanced statistical models, ensures the plan is grounded in post-pandemic realities. The key takeaway is that the resulting strategic principles, prioritizing sustainable transport, proposing concrete solutions for the congested inner ring road, and proactively managing freight transit, are not arbitrary goals. Instead, they are direct, evidence-based responses derived from a deep understanding of the city's actual mobility patterns. This data-driven methodology proves essential for transforming complex urban challenges into a clear, actionable roadmap. It provides Žilina with a robust framework for building a more sustainable and resilient transport system, ultimately enhancing the quality of life for its residents and ensuring the city is prepared for future growth.

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