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Model of transport, emissions, and weather relationships for selected territorial units

Disertation thesis

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Declaration

I hereby declare I have written this doctoral thesis independently and quoted all the sources of information used in accordance with methodological instructions on ethical principles for writing an academic thesis. Moreover, I state that this thesis has neither been submitted nor accepted for any other degree.

In Prague, November 2025

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Abstract

Urban mobility in metropolitan areas is shaped by the combined pressures of increasing motorization, climate change, and growing environmental demands. Prague exemplifies this trend, where fluctuations in meteorological conditions significantly influence traffic dynamics and the resulting emissions. This dissertation addresses the need for integrated tools that are based on knowledge that can interpret the interplay between weather, traffic flow, emissions, and urban morphology. The main objective of the research is to design and validate a semantic Situation Model that captures these multidomain interactions and supports operational and strategic decision-making in urban transport management.

The study adopts a mixed methodological approach that combines empirical analysis and semantic technologies. Traffic data from the TSK Praha detector network, CHMI meteorological and emission measurements, and morphological characteristics derived from GIS datasets were harmonized and categorized within a structured ontological framework. The core of the method lies in an OWL-based ontology with SWRL rules that enables reasoning in four domains (meteorology, traffic, emissions, and morphology). Validation was conducted on two representative arterial streets in Prague (Legerova and Vrsovicka) using two temporal snapshots.

The results confirm strong and interpretable relationships between meteorological states and urban traffic performance. Extreme temperatures and precipitation events reduce traffic speed and alter flow conditions, leading to elevated emissions of CO, CO_2, NO_x, and particulate matter. The ontology successfully generated consistent situational inferences, identified high-risk conditions, and demonstrated adaptability across diverse urban morphologies and temporal contexts. Comparative analysis shows that while traditional models (e.g., COPERT) provide highly detailed numeric outputs, the semantic approach excels in transparency, explainability, and integration of heterogeneous datasets.

The dissertation contributes a new and extensible model for interpreting weather-transport-emission relationships in cities, offering practical value for urban planners, mobility managers, and digital-twin platforms such as Golemio. The findings support proactive traffic management, improved air-quality assessment, and the planning of resilient mobility strategies. Recommendations for future development include the ingestion of real-time data, temporal reasoning, and hybridization with predictive analytics.

Keywords: Smart Cities; Urban Mobility; Traffic Flow; Meteorology; Emissions; Ontology; Knowledge Graph; Semantic Reasoning; Urban Morphology; Prague; Air Quality; Sustainable Urban Mobility; Climate Adaptation.

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Finally, I extend my heartfelt thanks to my family and closest ones for their unwavering support, patience, and understanding throughout my studies. Their encouragement has been indispensable and greatly appreciated.

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List of Acronyms

ABox	Instance Layer.	29
AI	Artificial Intelligence.	18
API	Application Programming Interface.	25
AQG	Air Quality Guidelines.	8
CAMS	Copernicus Atmosphere Monitoring Service.	26
CFD	Computational Fluid Dynamics.	13
CHMI	Czech Hydrometeorological Institute.	4, 13
CO	Carbon monoxide.	7
CO$_2$	Carbon dioxide.	8
DIKW	Data{Information{Knowledge{Wisdom.	16
DPF	Diesel Particulate Filter.	9
DPP	Dopravní podnik hl. m. Prahy.	18
EC	European Commission.	10
EMDS	European Mobility Data Space.	18
EU	European Union.	3, 5
FIS	Fuzzy Inference System.	35
FN	False Negative.	79
FP	False Positive.	79
GIS	Geographic Information System.	48
IEA	International Energy Agency.	2
IoT	Internet of Things.	17
IRI	Internationalized Resource Identifier.	33

ITF International Transport Forum. 2

ITS Intelligent Transport Systems. 11

LoS Level of Service. 24

MaaS Mobility-as-a-Service. 11

NO_x Nitrogen oxides (NO + NO_2). x, 8

O_3 Ozone. 9

OICT Operator ICT, a.s.. 5

OWL Web Ontology Language. 17, 57

OWL 2 DL Web Ontology Language – Description Logic. 30

PM Particulate matter. 9

RDF Resource Description Framework. 17

ROPID Regionální organizátor pražské integrované dopravy. 18

SUMP Sustainable Urban Mobility Plan. 3

SVF Sky View Factor. 14

SWRL Semantic Web Rule Language. 57

TBox Conceptual Layer. 29

TN True Negative. 80

TP True Positive. 79

TSK Praha Technická správa komunikací hl. m. Prahy. 4, 11

UCL Urban Canopy Layer. 14

UHI Urban Heat Island. 12

VOCs Volatile Organic Compounds. 9

WHO World Health Organization. 7

WMO World Meteorological Organization. 13

ČSN Československé normy. 24

ČSÚ Czech Statistical Office. 1

Contents

Chapter 1

Introduction

This thesis is based on the smart city approach to thinking about the city perspective and daily functioning. The concept of smart city is a multidimensional system that covers different aspects of a city. In this thesis, the focus is on traffic flow in conjunction with environments such as meteorological aspects, emissions, and urban infrastructure (morphology) of the city.

1.1 Description of the problem

Urban areas worldwide are facing increasing challenges related to transport demand, environmental impact, and climate change. These issues are particularly severe in metropolitan areas such as Prague, where population growth, increased motorization, and changing climatic conditions put significant pressure on urban infrastructure, air quality, and therefore quality of life. This section explores the key aspects of this problem and connects global trends with the local context of Prague.

1.1.1 Urbanization and the case of Prague

Urbanization is one of the defining global trends of the 21st century. According to the United Nations and other studies, nearly 68% of the global population is expected to reside in urban areas by 2050 [1], [2],[3]. The rapid growth of cities puts increased pressure on transport systems, energy consumption, and the urban environment, among other things.

Prague is a prime example of this development at the regional level. Its population increased from approximately 1.3 million in 2021 to approximately 1.4 million in 2022 [4], reflecting its ongoing demographic and economic attractiveness. According to the Czech Statistical Office (ČSÚ), this growth is expected to continue in the medium term, resulting in an increase in the demand for mobility, housing and public services.

1.1.2 Mobility and rising motorization

Mobility is a key aspect of urban life. However, in Prague, as in many other European cities, the high proportion of people who use cars to commute creates significant challenges. Transport studies reveal that the average passenger car in Prague is occupied by only 1.3 people, indicating an inefficient use of road space and energy [4], [5], and the number of vehicles is increasing.

This increase in motorization leads to congestion, uses up land, and emits greenhouse gasses. The International Transport Forum (ITF) estimates that the transport sector as a whole is responsible for 23% of global CO_2 emissions [6]. Similarly, studies on the future of mobility, such as Future of Mobility 5.0, show that cars still account for around 70% of passenger kilometers traveled in urban areas, while growth in active and public transport remains insufficient [7].

1.1.3 Climate change and meteorological conditions

Climate change manifests itself in the form of more frequent extreme weather events, such as heat waves, heavy rainfall, and frost, which have a significant impact on urban transport [7].

In Prague, empirical studies confirm that meteorological conditions have a strong influence on traffic dynamics. Case studies conducted on the streets of Legerova and Vrsovicka revealed that temperature and rainfall directly affect the intensity of traffic flow and the average speed, consequently affecting emissions [4]. These findings highlight the importance of integrating meteorological factors into urban transport planning.

At the European level, the International Energy Agency (IEA) emphasizes that climate risks also threaten the resilience of energy and transport systems, highlighting the interdependence of these sectors [8].

1.1.4 Transport, Emissions, and Environmental Impacts

The link between transport and emissions is particularly evident in Prague. According to the Prague Climate Plan 2030, the city has committed to reduce CO_2 emissions by 45% by 2030 compared to 2010 levels, with the aim of reaching climate neutrality by 2050 [9]. Passenger cars have been identified as the main source of emissions in Prague's transport sector [10].

Monitoring reports indicate that progress is being made, with notable expansions in the integration of renewable energy (e.g. 6.5 MWp photovoltaic installations in 2022 and 13.4 MWp in 2023) and investments in electromobility and zero emission busses [11].

Research using knowledge graphs and fuzzy models has demonstrated the potential of integrating transport, emissions, and weather data to better understand and predict urban environmental dynamics [9]. This highlights the importance of advanced, data-driven versus knowledge-driven approaches in policymaking and urban management.

1.1.5 Strategic frameworks and policy commitments

Addressing the interconnected challenges of transport, emissions, and climate change requires alignment of strategic frameworks at the local, national, and international levels. Prague:

- The European Green Deal is an commitment of EU to achieve climate neutrality by 2050 and a reduction of 55% of emissions by 2030 [12].
- The Sustainable and Smart Mobility Strategy (2021) sets out the objective of reducing transport emissions by 90% by 2050. To achieve this, it is imperative that all major cities adopt Sustainable Urban Mobility Plans (SUMP) [13], [14].
- The Draghi Report (2024) emphasizes the importance of substantial investments in green transformation and transport decarbonization for maintaining Europe's competitiveness [15].
- Complementary frameworks, such as REPowerEU, serve to reinforce the emphasis on the integration of renewable energy sources and the assurance of energy security [16].

These strategies provide the policy direction and financial instruments necessary to transform Prague into a sustainable, resilient, and competitive metropolitan area.

The conclusion drawn from the preceding arguments is as follows:

The confluence of rapid urbanization, rising motorization, and climate change poses a critical challenge for cities around the world. In Prague, these pressures can be seen in the form of increased traffic congestion, degrading air quality, and an elevated risk of exposure to climatic hazards. Nevertheless, the existence of a comprehensive strategic framework, ranging from the Prague Climate Plan 2030 to the European Green Deal, offers a roadmap for addressing these problems.

Integration of transport, meteorological conditions, and emissions data into decision-making processes, in accordance with European and global strategies, presents Prague with the opportunity to serve as a model for sustainable urban mobility and climate resilience.

1.2 The aim of this thesis

The challenges described above (rise of urbanization, increased motorization, and the growing impact of climate change on common life) underscore the need for integrated, data- and knowledge-driven approaches to understanding and managing urban transportation systems. Strategic frameworks introduced at the European and municipal levels (including the European Green Deal, the Sustainable and Smart Mobility Strategy, and the Prague Climate Plan 2030) highlight the importance of reducing emissions, improving air quality, and strengthening cities' resilience against climatic and environmental risks.

Building on these strategic goals, this thesis designs a model that describes and quantifies the impact of meteorological conditions on traffic flow and transport-related emissions in urban environments. The City of Prague serves as the case study area. The model aims to provide deeper insight into how weather variables (e.g. temperature, precipitation, wind speed, and direction) affect traffic flow and speed and the resulting emissions of key pollutants (e.g. CO_2, CO, NO_x, and PM particles).

1.3 Main objectives of the model

The main goal of the thesis is to design and validate a model that captures the interaction between meteorological parameters, traffic dynamics, and emission outputs in a complex urban environment. The model is intended to contribute to academic research and practical applications in the management of sustainable urban mobility.
Specifically, the thesis aims to:

1. Analyze and present the influence of meteorological conditions on traffic flow and emissions in Prague.
   a. This includes quantifying the correlations between weather parameters and measured traffic indicators using empirical data from the TSK Praha and CHMI networks.
   b. The findings will demonstrate how climatic variability and extreme weather conditions (e.g., heat waves, frost, and heavy precipitation) can affect traffic efficiency and emission levels.
2. Define scenarios for more effective traffic management under varying meteorological conditions.
   a. By applying statistical modeling techniques, alternative scenarios (e.g., extreme temperatures, high-intensity traffic, or episodes of reduced air quality) will be identified to support proactive decision-making by city authorities.

   b. The goal is to improve the city's capacity to anticipate and mitigate the negative environmental and social impacts of traffic, particularly during extreme weather events.

3. Support strategic and operational planning in line with sustainable mobility and climate strategies.
   a. The model will provide insights that can be directly integrated into the Sustainable Urban Mobility Plans and the Prague Climate Plan. This will help to evaluate the effectiveness of specific measures, such as low-emission zones, adaptive traffic management, and the promotion of active mobility during adverse conditions.
   b. Thus, it will contribute to the larger European objective of reducing transport-related emissions by 90% by 2050.

1.4 Expected contribution

The proposed model will serve as a decision support tool for urban planners and policy makers, enabling them to make more informed assessments of how meteorological variability influences urban traffic patterns and air quality. By integrating multi-domain data, such as traffic, meteorological, and emission datasets, the model will provide more accurate estimates of future transportation conditions. This will facilitate:

- Predictive traffic management to improve the responsiveness of city transportation systems in extreme conditions.
- Evidence-based emission forecasting to support compliance with environmental and climate goals.
- Enhanced quality of life for citizens through reduced congestion, emissions, and exposure to harmful pollutants.

The thesis aims to strengthen the knowledge base for sustainable and resilient urban mobility planning, aligning with the EU's vision of climate neutrality and the strategic ambitions of the city of Prague.

1.5 The motivation of the author

The author is motivated by long-term professional experience in urban mobility and smart city development in Prague in the municipal company Operator ICT, a.s. (OICT. Practical experience in these areas revealed a gap between strategic goals, such as climate neutrality, sustainable transportation, and resilience, and the analytical tools needed to implement them. The proposed model reflects the author's goal of making scientific insights usable for data- and knowledge-driven decision-making in cities.

The interdisciplinary nature of the topic, which combines transport engineering, meteorology, and environmental science, also drives the work. Understanding these interconnections allows for more comprehensive and adaptive planning.

Finally, the motivation is to improve urban resilience. By modeling extreme conditions, the research contributes to the city's preparedness and supports Prague's broader goals.

1.6 Research questions

Although cities are increasingly collecting large volumes of traffic, meteorological, and environmental data, these datasets are often analyzed separately. The absence of an integrated analytical framework creates a knowledge gap, or a missing link, between understanding meteorological variability, traffic dynamics, and emissions in real urban conditions.

This thesis aims to bridge this gap by developing a model that connects these domains and informs practical decisions for sustainable urban mobility and climate adaptation. Based on this motivation, the research addresses the following core questions:

1. How do different meteorological conditions in various parts of the urban area influence traffic flow and its negative environmental impacts?
2. How can the relationships between key variables (e.g., meteorological conditions, traffic flow, and emissions) be effectively defined and modeled? Identify statistical and causal links using empirical data and analytical modeling techniques.
3. What types of data (such as formats, collection frequency, time series structure) are required to establish reliable relationships between these variables?
4. How can research findings be applied to urban planning and traffic management to support evidence-based decision-making and improve resilience? Translate the output of the model into actionable insights for city authorities.

Chapter 2

Emission pollutants

This chapter introduces the types of air pollutants addressed throughout this work. The goal is to define the term and explain its connection to urban mobility and environmental pollution.

2.1 Carbon monoxide (CO)

Carbon monoxide (CO) is a gas that is colorless and odorless. It is produced when things are burned but not completely burned. When inhaled, CO attaches to hemoglobin, a protein in the blood. This makes it difficult for our bodies to get the oxygen we need. It can cause heart problems and other health problems. The WHO's 2021 guideline derives its new short-term value from a meta-analysis linking CO with myocardial infarction [17].

Vehicle exhaust, especially during cold starts, rich mixtures, idling, and stop-and-go driving, is the main source of urban CO. Modern three-way catalysts are effective in reducing CO emissions under these conditions but do not completely eliminate it. The development of the WHO guideline is based on evidence from multi-city time-series and meta-analysis [17].

The rate of reaction of CO is slow, on a chemical time scale, in the urban boundary layer (due to oxidation; with a lifetime measured in weeks to months). Thus, near-road patterns reflect emission and dispersion. Street-canyon trapping is an example of this. Low wind and stable layers also lead to accumulation [18].

Health-critical values (WHO Air Quality Guidelines 2021) [17], [19], [20]:

- 24h mean: 4 mg per m^3 (99th percentile, 3–4 exceedance days per year).
- Short averaging times retained from earlier WHO guidance (still valid): 8 h 10 mg per m^3, 1 h 35 mg per m^3, 15 min 100 mg per m^3.

WHO in AQG 2021 quantifies 5% higher admissions to myocardial-infarction on a day of 4 mg per m^3 vs. 1.15 mg per m^3.

2.2 Carbon dioxide (CO_2)

Carbon dioxide is a gas that is neither colorless nor odorous. It is the main greenhouse gas that humans have created and is released into the atmosphere when we burn carbon-based fuels. Although not toxic at ambient concentrations, carbon dioxide contributes to global warming, urban heat stress, and indirect health burdens through climate-mediated pathways [21], [22].

In urban areas, CO_2 emissions are significantly contributed by road transport, which is directly proportional to fuel consumption and the intensity of vehicle energy. According to emission inventories, road transport accounts for approximately 69% of total CO_2 emissions in the transportation sector globally [23]. Electric mobility has the potential to reduce emissions in the power sector, but this is only true if the generation of electricity does not involve significant carbon emissions.

CO_2 is a well-mixed, long-lived gas with an atmospheric life that stretches from decades to centuries. In urban boundary layers, spatial variations (typicallypm10{50 parts per million [ppm] above the background) reflect emission density and boundary layer height rather than local chemistry [24]. Nighttime inversions can trap CO_2 near the surface, but convective mixing disperses it vertically during the day.

The WHO does not have an air-air guideline for CO_2. This is because typical outdoor CO concentrations$_2$ (420{700 ppm) are far below direct toxicity thresholds (>5,000 ppm; occupational 8 h). CO_2 is relevant for climate rather than toxicity.

2.3 Nitrogen oxides ($NO_x = NO + NO_2$)

High combustion temperatures form nitrogen oxides through the oxidation of atmospheric nitrogen (thermal NO) and fuel nitrogen. Fresh exhaust consists primarily of nitric oxide (NO), which oxidizes in the atmosphere to form nitrogen dioxide (NO_2) [25]. NO_2 is directly harmful to health and contributes to the formation of photochemical ozone.

NO_2 is generated from the combustion of fossil fuels, including sources such as transportation, industrial processes, and other activities. It has become one of the most notable ambient air pollutants associated with health effects [26] Road vehicles remain the dominant source of NO_x emissions in urban areas. The intensity of emissions depends on the engine load, speed, fuel type, and after-treatment efficiency. Even under Euro 6/VI standards, diesel engines typically emit more NOx than gasoline engines [27]. The occurrence of cold starts and the phenomenon of stop-and-go driving serve to exacerbate emission factors.

Immediately after being emitted, NO reacts with ozone ($O_3 + NO \rightarrow NO_2 + O_2$), leading to depletion of ozone near roads. In the presence of sunlight and Volatile Organic Compounds (VOCs), NO_2 photolysis regenerates NO and radicals, which promote the formation of secondary ozone and nitrate aerosols [28]. The dispersion is strongly influenced by wind speed, street-canyon geometry, and boundary-layer stability. Low wind speeds and inversions cause accumulation near the surface. Health-critical values (WHO 2021) [17], [19], [20]:

- Annual mean: 10µg per m^3
- 24h mean: 25µg per m^3
- 1h mean (retained): 200µg per m^3

Elevated exposure to NO_2 is associated with the incidence of asthma and reduced lung function, with relative-risk increases of 4–5% per 10µg per $year^3$ annual increment.

2.4 Particulate matter ($PM_{2.5}$ / PM_{10})

The term "particulate matter" (PM refers to solid or liquid particles suspended in air. The size of these particles is measured in aerodynamic diameter. $PM_{2.5}$s less than 2.5 µm (fine), and PM_{10} is less than 10µm (coarse). Its components include black carbon, organic carbon, sulfates, nitrates, trace metals, and crustal material [18].

Traffic produces PM in the following ways:

- Exhaust emissions (soot and organics from incomplete combustion)
- Non-exhaust emissions, such as brake, tire, and road wear, as well as resuspension.

With the introduction of diesel particulate filters (DPFs), non-exhaust sources now dominate in many cities [29]. Emission factors vary by vehicle mass, speed, and driving pattern.

Fine particles have the capacity to remain in the atmosphere for extended periods, spanning hours or even days, traversing vast distances of tens of kilometers. However, coarse particulate matter usually precipitates more quickly. PM levels rise under stable meteorological conditions and in street canyons, where dispersion is limited. Particles are removed by wet scavenging (precipitation) and dry deposition. The settled dust is resuspended by traffic turbulence [18].

Health-critical values (WHO, 2021) [17], [19], [20]: • $PM_{2.5}$: Annual: 5 µg/m^3; 24h: 15 µg/m^3 • PM_{10}: Annual: 15 µg/m^3; 24h: 45 µg/m^3 Each 10 µg/m^3 increase in $PM_{2.5}$ is associated with a 6% increase in all-cause mortality.

2.5 Ozone (O_3)

Ozone is a secondary photochemical oxidant formed through the reaction of nitrogen oxides (NO_x) and volatile organic compounds (VOCs) in the presence of sunlight. Although not directly emitted, ozone is the result of urban photochemistry and influences regional air quality [30].

Vehicle emissions provide key precursors (NO_x and VOCs), which are important to consider when assessing air quality. In densely populated urban areas, ozone levels (O_3) are reduced by nitric oxide (NO) titration, resulting in low concentrations near roads. However, higher concentrations are observed downwind, where photochemical production plays a dominant role. The response of O_3 to emission controls is determined by the transition between the VOC-limited and NO2-limited regimes [28].

Ozone levels reach their highest point during warm, sunny, and stagnant weather conditions. This phenomenon can persist for an extended period, even for several days, and its distribution is often confined to specific regions. The geometry of the urban environment affects the mixing and consequently the depletion of ozone at the pedestrian level [31].

Health-critical values (WHO, 2021) [17], [19], [20]:

- Peak season (6 months) mean of daily maximum (8 h): 60 µg/m^3
- Daily maximum (8 h): 100 µg/m^3

Short-term exposure (by an increase of 10 µg/m^3 in the mean of 8 h) increases respiratory mortality by 0.3%.

2.6 Urban transportation

Urban transportation systems are the backbone of modern cities. They enable the movement of people and goods, while also shaping air quality, energy demand, and spatial development. In Europe, private cars remain the dominant mode of transportation, although cities are increasingly promoting public transportation and active mobility to achieve sustainability and climate goals. According to the European Commission's (EC) Sustainable and Smart Mobility Strategy [32], passenger transport in European urban areas consists of approximately 60–70% car trips, 25–35% public transit, and 5–10% walking and cycling. However, this varies significantly depending on the density, topography, and policy interventions of the city. Dense historic cores typically have a higher share of walking and public transportation, while suburban districts depend on cars.

A systemic perspective on traffic flow in urban areas reveals a high variability in both space and time. The morning and evening peaks correspond to commuting patterns, causing congestion on major roads and intersections. Empirical studies (e.g. Beneš et al., 2024; "Exploring the Impact of Meteorological Conditions on Urban Traffic Dynamics: A Prague Case Study" [4]) demonstrate that the average number of people per car in large cities rarely exceeds 1.3, resulting in inefficient use of land and energy. In Prague, the analysis-based detector networks operated by TSK Praha Praha reveal different daily patterns: during rush hour, the traffic speeds in the central zones decrease to 20–30 km/h, while the outer districts maintain higher flow rates [4]. These dynamics lead to increased fuel consumption and pollutant emissions, particularly during stop-and-go traffic and at intersections with a high density of traffic signals.

The tension between mobility demand and spatial capacity is increasing in modern cities. The need for integrated solutions is driven by limited road space, parking constraints, and environmental objectives. Solutions such as Mobility-as-a-Service (MaaS), shared micromobility, and intelligent transport systems (ITS) are examples of these integrated solutions. Real-time data platforms such as Golemio in Prague are a game changer. They empower authorities to keep an eye on traffic flow, emissions, and weather conditions, allowing for more informed decision-making. Evidence from European contexts (e.g. POLIS, CIVITAS, ITF Transport Outlook) supports this, showing that making improvements to the mix of transportation modes, with a greater focus on low-emission options, and enhancing flow stability can lead to significant reductions in CO2 and NO_x emissions. These changes can also contribute to improved urban resilience and quality of life.

2.7 Meteorological parameters in urban environment

Meteorological conditions and/or urban microclimate are among the most influential external factors affecting traffic dynamics and emissions related to transportation. Temperature, precipitation, and wind influence driving behavior, pollutant dispersion, chemical transformation, and removal processes within the urban boundary layer. Therefore, understanding these variables is the key to modeling real-world mobility and emission scenarios in cities like Prague.

2.7.1 Air temperature

The air temperature is the measure of the kinetic energy of air molecules and a fundamental indicator of the thermal conditions in the lower atmosphere. It is typically measured 2 meters above ground level using standard meteorological shields [33].

Temperature affects traffic patterns and vehicle emission rates. Cold conditions increase engine friction and fuel viscosity and extend catalyst light-off times. These factors increase CO and NO_x emissions during initial minutes of operation [34].

In contrast, high ambient temperatures promote photochemical activity and improve ozone formation from NO_x and VOC precursors [35].

Empirical research in Prague confirmed a strong correlation between temperature anomalies and traffic speed, indicating behavioral adaptation—drivers reduce speed during extreme heat or frost conditions [4].

In dense urban areas, the effect of urban heat island (UHI) increases nighttime temperatures by 2–6 °C compared to rural areas, altering thermal turbulence and pollutant mixing [36]. Local temperature gradients are determined by surface materials, vegetation, and morphology. These temperature gradients interact with transport emissions and energy fluxes.

2.7.2 Precipitation

Precipitation includes all hydrometeors that reach the ground, including rain, snow, sleet, and hail. Precipitation is measured in millimeters of equivalent liquid depth per unit of time (typically millimeters /h or millimeters /day) [33].

Rainfall directly affects road friction, visibility, and driver behavior, leading to measurable decreases in traffic performance. Studies in major metropolitan areas show that moderate rainfall can reduce speeds by 5–10% on urban arterials, and heavier rain can reduce speeds by 10–15% [37].

From an emissions and dispersion perspective, slowdowns in traffic caused by precipitation increase travel times and alter engine load cycles (i.e., more idle and low-speed operation). This increases the emissions per kilometer. Meanwhile, wet deposition and surface wash-off remove particulate pollutants from the atmosphere. Reduced vehicle speeds can also shift emission profiles (e.g., higher CO_2 and NO_x emissions per kilometer). These combined dynamics make precipitation an important meteorological variable in urban traffic emission modeling. Therefore, in model formulations, rainfall must be treated as a continuous variable reflecting intensity, duration, and spatial distribution rather than just as a binary event (rain or no rain) [37].

In Prague, the analysis showed that precipitation events (1 mm/h) led to an average decrease of 8-12% in mean speed on major arterials, such as Legerova Street. This finding is consistent with results from other European cities [4].

Rain and snow efficiently remove $PM_{2.5}$ and soluble gasses from the air through wet deposition processes [18]. The washout coefficient for fine particles increases exponentially with precipitation intensity, which contributes to short-term improvements in air quality after heavy rainfall events.

2.7.3 Wind speed and direction

Wind is the horizontal movement of air, defined by its speed (in meters per second) and direction (in degrees from north). Meteorological stations record 10-minute or hourly averages at a height of 10 meters, following WMO standards [33].

Wind speed and direction are central to the dispersion and dilution of traffic-related pollutants within urban street canyons. Elevated wind speeds improve ventilation by increasing the exchange of air between the canyon and the overlying atmospheric flow. This reduces the concentrations of NO_2, CO, and PM near the road [38]. In contrast, calm or low wind conditions (e.g., less than 1.5 m/s) combined with stable atmospheric layers hinder ventilation. This leads to the accumulation of pollutants and reduced visibility, as evidenced by reviews on urban canyon microclimates [39].

Furthermore, wind direction determines which side of the canyon or neighborhood receives traffic emissions. Perpendicular flows relative to the canyon axis can generate recirculation vortices and trap pollutants, while winds along the canopy flush emissions [38].

In Prague, for example, although specific local studies are limited, the northwest wind tends to ventilate the central corridors of the city. The south winds or stagnant wind regimes, on the other hand, align with high-pollution episodes, reflecting the broader mechanistic understanding of canyon ventilation behavior. Analysis of CHMI data shows that the northwest winds (prevailing) ventilate Prague, while the south stagnation corresponds to pollution episodes [4].

The complex morphology of the buildings creates recirculation zones through flow separation and vortex formation, trapping pollutants on the leeward sides of the streets [40]. Computational fluid dynamics (CFD) and field studies reveal that a canyon aspect ratio (Height / Width) greater than 1.5 strongly suppresses ventilation efficiency.

2.8 Urban morphology

Based on previous investigations, urban morphology was identified as a fundamental factor influencing the processes under study. Thus, this dissertation incorporates a morphological analysis to provide a more comprehensive assessment of the urban form and its impacts.

Urban morphology is the study of the spatial structure, geometry, and physical form of the built environment, including building height, density, street orientation, and open space distribution. Urban morphology defines how cities interact with energy, air flow, and pollutant dispersion [41], [42]. The morphological layout determines the local aerodynamic roughness and modifies the exchange of momentum, heat, and pollutants between the urban canopy and the atmosphere.

Typical parameters used to describe urban morphology include [43]

- Building height (H) and street width (W), often expressed as the aspect ratio (H/W);
- Plan area density (p) and frontal area density (f), which represent the proportion of built surfaces that affect air flow;
- Sky view factor (SVF) indicates the openness of the street canyon to the sky hemisphere.

The urban form directly impacts traffic performance and energy efficiency. High-density areas with narrow canyons in the street restrict traffic flow, limiting natural ventilation, and leading to congestion, heat accumulation, and the accumulation of pollutants [44]. On the other hand, larger boulevards and connected open spaces facilitate traffic circulation and pollutant dispersion.

Empirical analyzes demonstrate that the geometry of the street canyon can alter near-road pollutant concentrations by an order of magnitude. For example, in [45] it was demonstrated that NO_2 concentrations can increase by up to 70% in deep canyons (H/W > 1.5) compared to open roads due to limited vertical exchange. Similarly, the orientation of the street relative to the prevailing wind direction significantly influences the ventilation efficiency and the residence time of the pollutant [46]. These findings highlight the importance of incorporating morphological parameters into emission and dispersion models to achieve accurate urban assessments.

At the micro-scale, thermal and aerodynamic heterogeneity is driven by urban morphology. The Urban Canopy Layer (UCL) (the lowest layer of the urban atmosphere, extending from the ground to the roof level) exhibits different regimes of turbulence and radiation depending on its geometry. Narrow densely built canyons trap longwave radiation at night. This amplifies the effect of Heat Island in the city. Increases night air temperatures by 2 6 C compared to open areas [36].

During the day, the turbulence caused by the building's structure can increase the mixing of air in different layers. This happens when there are moderate winds. In low winds, pollutants (substances that pollute the air) are trapped near the ground. This happens because of vortices (rotating air currents) that are formed when the air is separated and then moves back towards the ground [40], [46]. The way in which air quality varies in space and how much urban populations are exposed to it are determined by these processes taken together.

Chapter 3

State Of The Art

The development of smart cities increasingly depends on the ability to integrate, interpret, and reason over complex datasets from multiple domains, such as transportation, the environment, energy, and meteorology. However, traditional data systems often remain isolated and semantically ambiguous. To address these challenges, researchers have introduced ontology-based models and knowledge graphs, which enable semantic interoperability and cross-domain data fusion.

This chapter reviews the current state of ontology engineering and knowledge graph applications in the context of smart cities. The chapter outlines the theoretical foundations of the DIKW model (data{information{knowledge{wisdom), highlights international case studies that demonstrate practical implementations, and discusses the limitations of existing approaches. The final section focuses on Prague's potential integration of knowledge-graph technologies into its Golemio data platform, establishing a conceptual foundation for the methodological framework presented in later chapters.

3.1 Ontologies and knowledge graphs

Ontologies and knowledge graphs are the technological foundation for enabling semantic interoperability across heterogeneous information systems in the Smart Cities domain.

Ontologies are formal, machine-interpretable conceptualizations of entities and their relationships. Knowledge graphs instantiate these conceptual models through interlinked data that describe objects, events, and contexts in the real-world [47], [48].

This approach follows the DIKW (data{information{knowledge{wisdom) hierarchy. Raw data is progressively structured, semantically enriched, and contextualized to obtain actionable knowledge for urban management [49]. Within this model, ontologies provide the structural layer (schema and vocabulary), and knowledge graphs connect data points across domains such as mobility, environment, and energy to form the dynamic layer.

Semantic interoperability is critical for smart city ecosystems, which integrate heterogeneous data from multiple stakeholders, including municipal authorities, transportation operators, energy utilities, and meteorological services. A review of the literature on semantic technologies in smart cities was conducted in [50]. The review found that the lack of shared vocabularies and formal ontologies remains a primary barrier to the full integration of IoT (Internet of Things) and urban data systems. Adopting shared vocabularies and linked-data principles (such as RDF, OWL, and SPARQL) enables knowledge graphs to perform cross-domain reasoning and automate the discovery of relations among otherwise siloed datasets.

3.2 Knowledge graphs in Smart City Context

Recent research and operational deployments demonstrate the role of knowledge graphs as integration and reasoning engines in smart cities. For example, [51] describes a knowledge graph{based data integration system that links heterogeneous sensor streams, built assets, and environmental data to support digital twins in urban contexts. In Europe, the SynchroniCity initiative established harmonized data models and marketplace architecture to promote IoT between cities and standardization of data services.

At the research level, a systematic review of smart city ontologies and their applications shows how ontology- and graph-based approaches enable the cross-domain integration of mobility, energy and environmental data.[54]

Other relevant case studies include:

- The City Data Hub, a standard-based platform for smart city data sharing and knowledge graphs [52];
- The European Commission's proposal for a European Framework for Interoperability for Smart Cities and Communities sets the policy and structural basis for data and service-level interoperability across cities [53].

3.3 Ontology{Graph Synergy

Ontologies and knowledge graphs form a complementary pair: ontologies provide a formal structure, while graphs illustrate these relationships using real data. This synergy enables reasoning, which is the process of deriving new facts from existing data using semantic rules or graph-based algorithms. For example, one can infer emission hotspots from correlated meteorological and traffic nodes.

Through technologies such as reasoning and graph embeddings, cities can automatically detect anomalies, discover correlations, and suggest interventions in mobility or environmental management [54].

In practical smart city deployments, this reasoning capacity underpins decision support systems, enabling scenario modeling ("what if" analysis) and cross-domain alerts (e.g., predicting ozone peaks during congestion).

3.4 Limitations of Existing Solutions

Despite substantial progress, current implementations face several limitations:

- The heterogeneity of the data models between cities and vendors still hampers full interoperability.
- Scalability issues arise with high-frequency IoT streams.
- Lack of standardized ontologies for certain domains (e.g., meteorology{mobility interactions);
- Governance and data-sharing barriers also pose challenges, particularly in municipal environments where there are legal constraints on data privacy.

Most existing frameworks focus on structural integration. However, they provide limited support for temporal reasoning, uncertainty modeling, and city-specific contextualization [58]. These gaps provide an opportunity to develop domain-specific ontologies tailored to the context of integrated mobility, emissions, and meteorology in Prague [55].

3.5 Context of Prague

In Prague, the Golemio data platform, operated by the municipal company OICT, provides a central hub for city-scale data integration, analytics, and visualization. Golemio currently consolidates data from transportation operators (TSK Praha, DPP, and ROPID, etc.), environmental sensors, and open data sources.

The next step is to enrich these datasets with semantic layers to allow automated linking of traffic flow, weather conditions, and emission output. This aligns with European initiatives, such as the European Mobility Data Space (EMDS) and the AI Act{compliant Smart City Data Governance.

Integrating a knowledge graph layer into Golemio would enable the following:

- Cross-domain queries (e.g., retrieving NO_2 peaks correlated with rainfall intensity and traffic density).

- semantic reasoning for urban resilience indicators;
- interoperability with EU data space ontologies.

Thus, Prague's context is ideal for testing how ontology-based data integration can improve operational smart city platforms.

Chapter 4

Methodology and model design

The methodological framework of this dissertation is based on the holistic integration of data analytics, semantic technologies, and knowledge representation. It is designed to capture the complex interdependencies between transportation, meteorological conditions, and emission dynamics in an urban environment.

The primary outcome of this approach is the Situation Model, a semantically driven reasoning framework in Protégé software that can interpret data from multiple domains through formally defined relationships and rules.

Figure 4.1 illustrates the conceptual architecture of the proposed methodology and reflects the author's approach to modeling and reasoning across heterogeneous domains.

The framework begins with heterogeneous data gathering in the first stage, including multiple urban domains. These datasets originate from institutional and sensor-based sources, including TSK Praha, CHMI, OICT (Golemio) and other open data systems.

Due to their varying temporal resolutions, formats, and quality, the initial step is to clean and preprocess the data to ensure completeness, consistency, and interoperability. This step includes removing outliers, imputing missing values, aligning data temporally, and normalizing measurement units.

The second stage focuses on data categorization and domain standardization, where continuous variables are transformed into linguistic categories and standardized according to domain-specific methodologies. This process not only facilitates interpretability, but also provides a structured basis for semantic modeling in subsequent stages.

The third methodological layer comprises statistical correlation and causality analysis, through which relationships between individual variables are explored and quantified. The analysis employs both descriptive and inferential techniques (e.g., Pearson correlation) to identify significant dependencies among different domain data sets. These verified relations form the foundation for defining semantic rules and axioms within the ontological model.

Figure 4.1: Conceptual Framework of the Situation Model — adapted from Beneš et al., 2024, Neural Network World

At the core of the framework lies the Situation Model, representing the original scientific contribution of the author. This model, implemented as an ontology in Protégé software, enables the integration, reasoning, and interpretation of multi-domain data. By semantically linking traffic, emission, and meteorological entities in the urban environment, the Situation Model can infer cross-domain impacts and provide context-sensitive evaluations (e.g., identifying conditions of limited dispersion, high emission load, or meteorological stagnation). Unlike previous studies, this research introduces a fully ontology-based reasoning framework that operationalizes empirically derived relationships across transport, meteorology, and emission domains in an urban environment.

The resulting knowledge graph thus becomes a living analytical structure capable of dynamically reflecting urban conditions through reasoning and inference.

Finally, the decision and application layer converts the model's output into actionable insights for urban management. These insights can inform adaptive transportation policies, such as dynamic parking pricing, emission-sensitive traffic regulation, and prioritizing public transportation corridors under specific weather conditions.

This final layer shows how semantic reasoning can bridge the gap between data-driven analytics and policy-relevant decision-making. Provides a foundation for the creation of intelligent and resilient urban mobility systems.

In general, the conceptual framework in Figure 4.1 combines classical data processing methodologies with semantic reasoning to create an interpretable, transferable model. This framework represents a methodological advancement that transforms fragmented urban datasets into a coherent, knowledge-based system capable of descriptive analysis and prescriptive insight generation.

4.1 Data preprocessing and harmonization

The success of the proposed methodological framework depends on the quality and structure of the underlying data.

In urban systems research, data are often fragmented across multiple institutional sources, stored in different formats, and collected at various temporal resolutions. Therefore, before these datasets can be integrated into a unified knowledge graph and interpreted semantically by the Situation Model, they must be rigorously preprocessed, harmonized, and validated.

4.1.1 Data sources and heterogeneity

The study integrates datasets from several key institutional and open-data sources representing three major domains:

- Traffic domain: Technical Administration of Roads (TSK Praha) and Operator ICT (OICT/Golemio);
- Meteorological domain: Czech Hydrometeorological Institute (CHMI);
- Emission domain: The CHMI air quality monitoring network.

Each dataset differs in structure and periodicity. The TSK detectors provide five-minute level traffic flow, whereas CHMI meteorological observations are typically recorded hourly and emission concentration data are reported in $\mu g\ m^{-3}$ with hourly or daily averages. Due to differences in granularity, completeness, and coordinate reference systems, a consistent methodological approach is necessary to ensure cross-domain comparability.

4.1.2 Data cleaning and validation

The first preprocessing phase involves data quality control, including the detection and correction of missing or anomalous values. Outliers are identified through box plot and interquartile range analysis and then compared with reference statistical distributions from similar locations. Short gaps (less than two hours) are filled by linear interpolation or local mean substitution. Longer discontinuities are excluded to avoid bias in temporal correlations.

Traffic data is particularly vulnerable to discontinuities due to sensor outages or communication errors. Problematic locations, such as Prague–Karlín, have been identified as areas with technical interruptions that lead to incomplete time series. For these areas, either supplementary data from nearby stations can be modeled, or these stations can be removed from the list.

Figure 4.2: Map of Prague includes transportation (Traffic strategy detectors) and meteorological and emission detectors (CHMI sensors)

The fundamental principle is to maintain the integrity of time series data because it is imperative to identify correlations and causal relationships across domains.

4.1.3 Temporal and spatial alignment

To ensure comparability and integration across the three domains of transportation, meteorology, and emissions, which change over short periods of time, a systematic temporal and spatial alignment procedure was applied to all datasets. This step aimed to create a unified analytical time series that maintains spatial relevance and temporal coherence between all monitored variables.

Spatial alignment

First, measurement sites were identified in the studied area of Prague. Each traffic detection point (traffic strategy detectors) was matched with its nearest corresponding meteorological and emission measurement sites (CHMI sensors). This ensured that all compared datasets referred to comparable spatial contexts. See figure 4.2.

Temporal alignment

In order to standardize all data to a common one-hour resolution, which was deter-