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# Assessing the Impact of Zurich's Road Noise Mitigation Plan on Public Transport

GEO 511 Master's Thesis


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## Abstract

Road noise presents an ever-growing urban challenge, with associated health risks such as cardiovascular diseases and diabetes. In Zurich, approximately 125,000 residents—28% of the population—are exposed to noise levels that exceed regulatory thresholds. To address this issue, the city council introduced the Road Noise Mitigation Plan (RNMP), which aims to implement speed limits of 30 km/h on designated roads to reduce noise levels throughout the city. This master's thesis, conducted in collaboration with Verkehrsbetriebe Zürich (VBZ), examines the impact of the planned RNMP on public transport. The statistical analysis revealed that reduced speed limits significantly affect bus travel times, while trams remain largely unaffected, primarily due to the presence of independent rail bodies. Substantial differences were not observed between the peak hours of morning and evening traffic. The study points out that the most affected bus line experience delays of up to five minutes, requiring frequency adaptations along with operational adjustments to reduce additional travel times. The study therefore also assessed stop modifications (removal or consolidation) using a case study of the two tram-stops *Löwenbräu* and *Quellenstrasse*. This evaluation examined changes in walking distances using elevation-adjusted speeds, highlighting possible trade-offs between optimizing travel times and maintaining accessibility. By quantifying the operational consequences of 30 km/h speed limits and their spatial implications, this study provides valuable insights for future public transport planning.

**Keywords:** Road Noise Mitigation Plan, Speed reduction, Tempo 30, Travel times, 30km/h, Road Noise, Public Transport, Accessibility, Stop relocation

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# Abbreviations

| Abbreviation | Definition |
|---|---|
| EPA | Federal Environmental Protection Act (German: Umweltschutzgesetz) |
| GWR | Building and Housing Register (German: Gebäude- und Wohnungsregister) |
| HVZ | Traffic peak hour (German: Hauptverkehrszeit) |
| NAO | Federal Noise Abatement Ordinance (German: Lärmschutzverordnung, LSV) |
| RNMP | Road Noise Mitigation Plan (German: Umsetzungsplanung Strassenlärmsanierung) |
| T30 | Speed limit of 30 km/h |
| T50 | Speed limit of 50 km/h |
| UBK | Independent rail bodies (German: Unabhängige Bahnkörper) |
| VBZ | Public Transport Operator in the City of Zurich (German: Verkehrsbetriebe Zürich) |
| WHO | World Health Organization |

**Table 1:** List of abbreviations used in this study.

# Chapter 1

# Introduction

## 1.1 Motivation

The challenges associated with urban traffic management extend well beyond considerations of mobility and economic efficiency, encompassing significant implications for public health and environmental sustainability. One of the most notable consequences of traffic is environmental noise pollution, which has gained increasing recognition as a critical public health concern (Basner et al., 2014; Boer and Schroten, 2007). Environmental noise, defined by the World Health Organization (WHO, 2018) as noise from all sources excluding occupational noise, is a pervasive pollutant with significant implications for health and well-being (World Health Organisation, 2018; Perna et al., 2022; Guski et al., 2017).

The largest contributor to environmental noise is road noise, generated by motorized street traffic such as cars, trucks, motorcycles, buses, and trams (Stadt Zurich, 2022). Increasingly recognized as a critical public health concern, road noise plays a unique role in shaping the environmental quality of cities due to its widespread prevalence and close connection to urban mobility (Basner et al., 2014; Boer and Schroten, 2007).

Given its widespread presence and substantial impact, road noise poses severe psychological and physiological health challenges, as highlighted by the WHO (World Health Organisation, 2018). Long-term exposure to road noise is associated with disrupted sleep patterns, significantly increasing the risk of hypertension, myocardial infarction, and stroke (Stansfeld et al., 2021; Huss et al., 2010; Vienneau et al., 2015; Sørensen et al., 2012). Moreover, growing evidence indicates that road noise contributes to higher rates of depression, cardiovascular diseases, and mortality. These findings underscore the urgent need for targeted mitigation strategies to address the health and societal consequences of road noise and to improve urban living conditions (Floud et al., 2013; Belojević, 2024; Stansfeld et al., 2021; Basner et al., 2014).

In recognition of the risks posed by road noise, many countries have introduced environmental legislation to address noise pollution and mitigate its detrimental health impacts (Naish, 2010;

Omerhodžić and Džaferović, 2021). In Switzerland, federal environmental law mandates that road owners implement measures to reduce noise pollution directly at its source. This regulatory framework aims to protect public health by minimizing harmful exposure to elevated noise levels (Bundesamt für Umwelt (BAFU), 2018). In densely populated urban areas such as Zurich, road noise exceeds legal thresholds across significant portions of the road network, making noise mitigation a pressing need. Approximately 125,000 residents—equivalent to 28% of Zurich's total population—are exposed to noise levels exceeding permissible thresholds. This widespread noise pollution raises significant concerns for public health and overall quality of life in the city (Stadt Zurich, 2022).

Lowering speed limits is a widely recognized approach to mitigating road noise, particularly in high-density urban areas. Research has shown that reduced speeds significantly decrease vehicle noise emissions, making it an effective strategy for noise control (Brink et al., 2022; Basner et al., 2014). To address the adverse effects of road noise on public health and urban quality of life, the City Council of Zurich introduced the Road Noise Mitigation Plan (RNMP). The first phase of the RNMP was implemented in 2012, introducing 30 km/h speed limits on various streets throughout the city. However, these initial measures mainly targeted residential streets with low traffic volumes, where major streets and public transport were not affected. Many of these streets had previously operated with reduced speed limits already, and noise levels did not exceed regulatory thresholds.

Now in its third phase, the RNMP aims to significantly reduce overall road noise levels across Zurich by extending 30 km/h speed limits to an additional 150 kilometers of the road network, including major streets with high public transport activity. Unlike previous phases, which primarily targeted residential streets, this phase directly affects key roads that are also used by trams and buses, marking a significant shift in its implementation. With a complete roll out planned for 2030, the RNMP seeks to substantially reduce road noise while balancing environmental sustainability, public health protection, and operational efficiency of Zurich's transportation system (Stadt Zurich, 2021b).

For streets where road noise levels remain excessively high, the RNMP includes additional measures in addition to speed reductions, such as the use of low noise paving and the promotion of electromobility until 2050 (Stadt Zurich, 2021b). However, these additional interventions fall outside the scope of this study, which focuses specifically on the impact of speed reductions on public transport.

The introduction of 30 km/h speed limits on urban roads can significantly influence travel times for public transport. This is primarily due to the reduction in maximum achievable speeds, which directly impacts the average speed of vehicles operating in mixed traffic. While public transport vehicles, such as buses and trams, rarely sustain maximum speeds over long distances due to frequent stops and signal interruptions, lower speed limits can still extend travel times, particularly on longer stretches between stops or in less congested areas. These changes, in turn, affect scheduling, operational efficiency, and passenger experience, making it a critical area for analysis (Verkehrs-Club der Schweiz (VCS), 2023).

## 1.2 Research Objectives

This master's thesis examines the impacts of Zurich's third-phase Road Noise Mitigation Plan on the city's public transport network, with a focus on two primary objectives.

The *first* objective is to evaluate how the reduced speed limits will influence travel times. To achieve this, a network-wide analysis of the impact on all VBZ-operated tram and bus lines is conducted using both descriptive and statistical methods. By examining shifts in speed regimes, the research aims to provide insights into the relationship between noise mitigation measures and the operational performance of public transport. The changes introduced by the RNMP will be compared against a reference period from April and May 2023, which was identified by VBZ experts as a period representative of typical network conditions across the year.[1]

The removal or consolidation of transit stops is a potential strategy to improve travel times and operational efficiency by reducing the number of deceleration and acceleration cycles and minimizing passenger boarding and alighting delays. However, this measure often comes at the cost of reduced accessibility, as the walking distance to transit stops increases. This trade-off is particularly significant in densely populated urban areas, where public transport relies on close proximity to stops to ensure widespread coverage. Additionally, the removal of stops tends to face strong public resistance, which limits its practical application (Verkehrs-Club der Schweiz (VCS), 2023).

On the other hand, fewer stops can also lead to time savings for passengers already on board, as overall travel times decrease due to fewer interruptions. This effect can enhance the efficiency of public transport, particularly on high-frequency routes where excessive stopping negatively impacts service reliability [2]. These competing factors highlight the importance of accessibility analysis to fully understand the potential impacts of stop adjustments on public transport users (Verkehrs-Club der Schweiz (VCS), 2023).

To better understand this trade-off, the *second* objective of this thesis examines how accessibility, defined as walking distance from transit stops to building entrances, changes under stop removal or consolidation scenarios. VBZ has considered such adjustments as a strategy to mitigate the additional travel time caused by 30 km/h speed limits[3]. By assessing the accessibility impacts of these measures, this study provides a framework for balancing operational efficiency with maintaining high accessibility standards.

This study places particular emphasis on the tram stops *Löwenbräu* and *Quellenstrasse*, which have been identified as key locations by VBZ experts due to their proximity and operational importance. These stops serve as a case study to examine how potential adjustments to the locations of transit stops could affect accessibility in the surrounding area and how these changes can be assessed. Using this targeted approach, the case study aims to offer practical insights to optimize transit stop configurations while ensuring minimal negative impacts on accessibility.[4]

[1]Discussion with VBZ experts, February 2024.
[2]Discussion with VBZ experts, January 2025.
[3]Discussion with VBZ experts, January 2024.
[4]Discussion with VBZ experts, August 2024.

## 1.3 Study Area

### 1.3.1 City of Zurich

The study area for this research is the City of Zurich, Switzerland's most populated city and the capital of the Canton of Zurich. As of October 2024, Zurich had a population of 449,315 residents spread over an area of 87.93 $km^2$ (Stadt Zurich, 2024). With its high population density and complex urban infrastructure, Zurich provides an exemplary case for examining the interplay between public transport operations and road noise mitigation policies.

### 1.3.2 Verkehrsbetriebe Zurich (VBZ)

This research is conducted in collaboration with Verkehrsbetriebe Zurich (VBZ), Zurich's public transport operator, leveraging its data and expertise to ensure a robust and contextually relevant analysis. The partnership facilitates access to extensive data sets and operational insights, ensuring that the study findings are both practically applicable and aligned with Zurich's broader urban planning.

The study focuses on the tram and bus network managed by Verkehrsbetriebe Zurich (VBZ), the city's municipal transportation operator. Founded in 1896 as the "Städtische Strassenbahn Zurich", VBZ now oversees most local public transport in Zurich and some regional lines, operating as part of the Zurich Transport Network (ZVV) since 1990. VBZ plays a crucial role in Zurich's mobility, operating a fleet of 490 vehicles that transport more than 860,000 passengers per day on 74 lines. VBZ vehicles collectively cover around 90,000 kilometers daily—more than twice the Earth's circumference—highlighting the scale of its operations and its central role in Zurich's public transport infrastructure (Verkehrsbetriebe Zurich, 2023).

| Daily Passengers | Track Network (km) | Transit Stops | Vehicles | Lines |
|---|---|---|---|---|
| 860,000 | 170 | 439 | 256 buses, 234 trams | 74 |

**Table 1.1:** Overview of key statistics for VBZ operations, including daily passenger numbers, track network length, number of transit stops, vehicles, and lines (Verkehrsbetriebe Zurich, 2023).

The route network map (Figure 1.1) provides an overview of Zurich's public transport system, including trams, buses, and regional lines. This thesis, however, focuses specifically on VBZ-operated tram and bus lines within the urban area during peak traffic hours. Accordingly, the analysis is limited to 13 tram, 22 bus and six trolley bus lines, excluding regional lines, the night network, the funicular railway, and tram line 12 (operated by Verkehrsbetriebe Glattal) (Verkehrsbetriebe Zurich, 2025).

The RNMP, including the gradual introduction of 30km/h speed limits, introduces significant changes that may impact VBZ's operations, such travel times and schedules. As a cornerstone of Zurich's urban mobility infrastructure, VBZ is particularly interested in understanding these implications to adapt its services and maintain efficiency. This research focuses on evaluating the plan's influence on public transport operations, providing insights to support VBZ's long-term planning and service optimization (Verkehrsbetriebe, 2025).

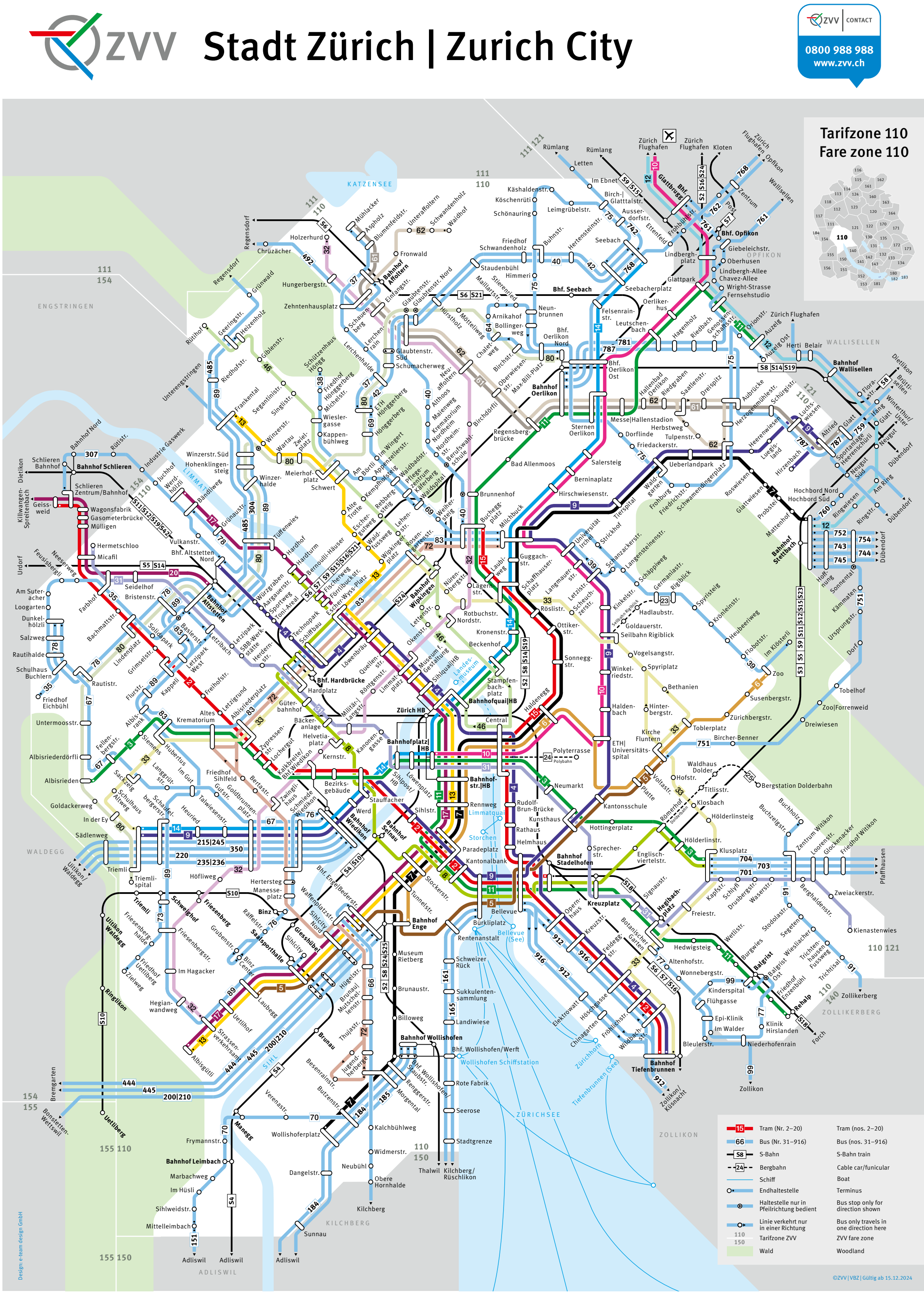



**Figure 1.1:** Public transport network of the City of Zurich

# Chapter 2

# Related Work

## 2.1 Background

### 2.1.1 Impacts of Road Noise on Public Health

Road noise is a widespread urban challenge with significant public health implications. Research indicates that prolonged exposure to high noise levels can disrupt sleep patterns and contribute to serious health conditions, including cognitive impairments, cardiovascular diseases, diabetes, and psychological disorders (Boer and Schroten, 2007; Stadt Zurich, 2022).

Historically, the health effects of noise pollution were primarily linked to annoyance, hearing damage, and other non-auditory effects (Basner et al., 2014). However, recent studies reveal a more complex relationship between chronic exposure to road noise and severe cardiovascular outcomes, including ischemic heart disease, hypertension, and stroke. These effects are shown to be independent of those caused by air pollution (Sørensen et al., 2012; Fritschi et al., 2011; Basner et al., 2014). These findings underscore the importance of integrating noise mitigation strategies into urban planning to address both immediate and long-term health risks.

Research carried out in Lausanne provides further evidence of the significant health impacts of road noise and the potential benefits of noise mitigation measures. Rossi et al. (2020) estimated that reducing speed limits to 30 km/h city-wide could prevent 1 cardiovascular death annually and significantly reduce high annoyance levels associated with noise for over 2,800 residents. Their findings highlight the broader public health benefits of speed reductions in mitigating the adverse effects of noise pollution (Rossi et al., 2020).

### 2.1.2 Economic Impacts of Noise in Switzerland

Traffic noise imposes substantial economic costs on Switzerland, many of which are external and not borne by the noise polluters. According to the Swiss Federal Office for the Environment (BAFU), the external costs of mobility-related noise amounted to approximately 2.5 billion Swiss francs in 2020 (Bundesamt für Umwelt (BAFU), 2018). Road noise alone accounts for the majority of these costs, estimated at two billion Swiss francs annually (Stadt Zurich, 2022).

These costs primarily comprise health expenses and property devaluation. Health-related costs, resulting from noise-induced physical and psychological conditions, accounted for approximately 1.4 billion Swiss francs (55%). This includes medical treatment, loss of productivity, and reduced quality of life (Bundesamt für Umwelt (BAFU), 2018). Property devaluation, estimated at 1.1 billion Swiss francs (45%), reflects the lower market prices of homes in noisy areas, as the public is willing to pay a premium for quieter residential environments (Bundesamt für Umwelt (BAFU), 2018).

In addition to these direct impacts, noise pollution discourages investment in affected areas, which can lead to urban decline. These economic and social consequences underscore the critical importance of implementing effective noise mitigation strategies to safeguard public health, preserve property values, and minimize the broader economic losses associated with environmental noise pollution.

### 2.1.3 Federal Environmental Protection Act

To address these risks associated with road noise, Swiss environmental law mandates road owners to implement noise reduction measures, prioritizing interventions at the source of the noise (Schweizerische Eidgenossenschaft, 2025). The Swiss Federal Environmental Protection Act (EPA, *German: Umweltschutzgesetz, USG*) establishes the legal foundation for protecting humans and the environment from harmful noise impacts, guided by the precautionary principle (*German: Vorsorgeprinzip*) and the polluter-pays principle (*German: Verursacherprinzip*) (Schweizerische Eidgenossenschaft, 2025).

The Federal Noise Abatement Ordinance (NAO, *German: Lärmschutzverordnung, LSV*) specifies noise exposure limits, with stricter thresholds for nighttime (10 p.m. - 6 a.m.) and residential areas. If these limits are exceeded, abatement measures must be planned and implemented to a reasonable and proportionate extent (Art. 17 EPA, Art. 8 para. 2 NAO). Priority is given to interventions at the source, such as speed reductions or noise-reducing surfaces (Art. 17 EPA, Art. 13 para. 3 NAO) (Schweizerische Eidgenossenschaft, 2025).

### Road traffic noise exposure limits

The City of Zurich is subject to the provisions of the NAO, which define exposure limits for road traffic noise. These limits vary according to the land-use sensitivity (sensitivity level) and time of day. The limits apply to noise generated by motor vehicles and railways that run in roadspace (e.g. trams) (Table 2.1).

| Sensitivity Level | Planning Value (Lr in dB(A)) | | Immission Limit (Lr in dB(A)) | | Alarm Value (Lr in dB(A)) | |
|---|---|---|---|---|---|---|
| | Day* | Night** | Day* | Night** | Day* | Night** |
| I (Recreational Areas) | 50 | 40 | 55 | 45 | 65 | 60 |
| II (Residential Areas) | 55 | 45 | 60 | 50 | 70 | 65 |
| III (Mixed-Use Areas) | 60 | 50 | 65 | 55 | 70 | 65 |
| IV (Industrial Areas) | 65 | 55 | 70 | 60 | 75 | 70 |

**Table 2.1:** Road traffic noise exposure limits according to the Noise Abatement Ordinance (NAO) (Schweizerische Eidgenossenschaft, 2025). *Day refers to the time period from 6 a.m. to 10 p.m.; **Night refers to the time period from 10 p.m. to 6 a.m.

If imission limits are exceeded, noise mitigation measures must be planned and implemented, provided they are deemed reasonable and proportionate, as stipulated in Article 17 of the EPA. When alarm values—significantly exceeding immission limits—are breached, immediate action is required due to the substantial health risks (Schweizerische Eidgenossenschaft, 2025).

## 2.1.4 Road Noise situation in the City of Zurich

Road noise represents a significant environmental challenge in Zurich. As shown in Figure 2.1, 27% of Zurich's population is exposed to imission limits exceeding the daytime limit of 60 dB and nighttime limit of 50 dB, while 1% endure alarming values above 70 dB (day) and 65 dB (night). Around 125,000 residents live in buildings where noise levels exceed legal thresholds. However, it is important to note that this number reflects the total number of people who reside in these buildings, regardless of whether specific rooms or apartments within the buildings are directly affected by elevated noise levels. As a result, the actual number of individuals experiencing high noise exposure may be slightly lower. Nighttime exposure poses an additional concern due to stricter noise standards enforced during these hours, further exacerbating the issue, as can be seen in Table 2.1 (Stadt Zurich, 2022).

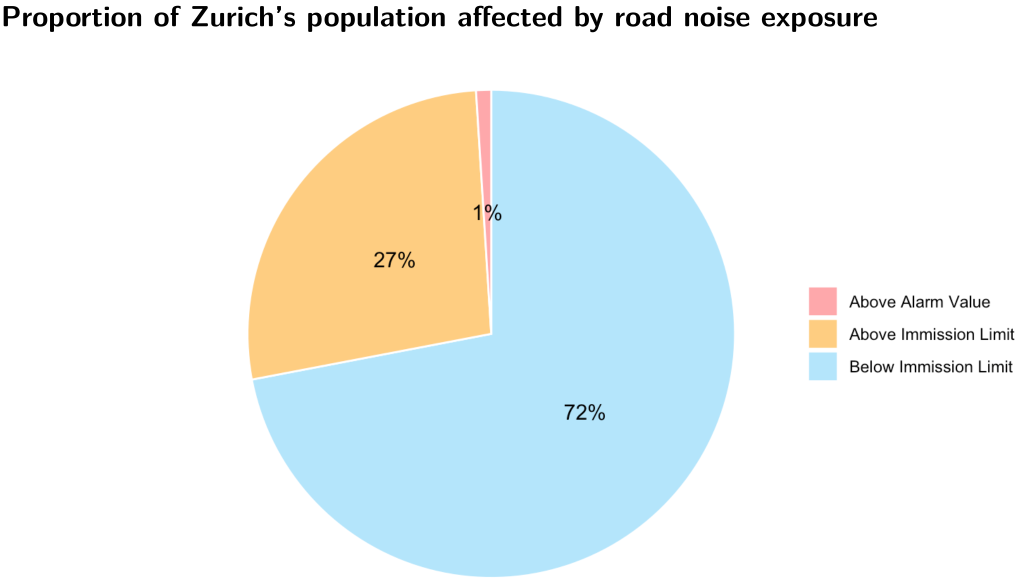



**Figure 2.1:** Proportion of Zurich's population affected by road noise exposure in 2022. (Own illustration based on data from (Stadt Zurich, 2022))

### 2.1.5 Road Noise Mitigation Plan (RNMP)

Zurich developed the Road Noise Mitigation Plan in 2012 to address the widespread problem of excessive road noise, which contravenes legal noise thresholds set by EPA and therefore impacts public health. The plan aims to mitigate noise at its source through targeted measures and phased implementation, improving urban quality of life while ensuring compliance with the NAO (Stadt Zurich, 2021a,b).

The first two phases of the RNMP aimed to reduce road noise by implementing speed limits of 30 km/h on selected street segments. These measures focused primarily on cars-dominated roads and residential neighborhoods with minimal public transport presence, ensuring that public transport remained largely unaffected during these initial phases (Stadt Zurich, 2021a,b; Kanton Zurich, 2025).

In December 2021, Zurich's City Council adopted the third phase of the plan (Council Resolution STRB 1217/2021). Unlike the earlier phases, this stage introduces speed limits of 30km/h on key streets that are also used extensively by trams and buses (Stadt Zurich, 2021b).

The overall effects of the RNMP on public transport operation remain unclear. This thesis, therefore, focuses specifically on the third phase of the RNMP, where the introduction of 30 km/h speed limits on tram and bus routes directly impacts VBZ's network.

### 2.1.6 Key Measures in the RNMP

#### Combination of Measures

The City of Zurich's RNMP employs a multi-faceted approach to noise reduction, combining targeted measures such as the introduction of 30 km/h speed limits, the implementation of low-noise road surfaces, and the promotion of electromobility to address noise at its source. Given the high noise pollution levels in certain areas, a combination of interventions is often required. These measures not only reduce noise exposure but also enhance public spaces, contribute to sustainable urban development, and improve overall quality of life for residents. The phased approach ensures measurable improvements over time and allows for adaptation of strategies as needed. By addressing both immediate and long-term noise challenges, Zurich sets a model for sustainable urban noise management and improved quality of life for its residents (Stadt Zurich, 2021b).

### Speed Reductions (*Tempo 30*)

Speed reductions implemented as part of the RNMP are among the most effective and cost-efficient measures for mitigating road traffic noise. Lowering speed limits from 50 km/h to 30 km/h reduces noise immission by approximately 3 dB, effectively halving the perceived noise level. This reduction not only decreases overall noise exposure but also minimizes peak noise levels, which are particularly disruptive at night, leading to sleep disturbances and awakening reactions (Stadt Zurich, 2021a; Kanton Zurich, 2025).

The current phase of the RNMP focuses on introducing 30 km/h limits[1] on heavily trafficked streets, prioritizing areas with excessive noise levels, particularly residential zones along major corridors. By the end of 2021, 37 kilometers of streets had been converted, with an additional 150 kilometers planned for implementation by 2030 (Stadt Zurich, 2021b). In Switzerland, two primary forms of 30 km/h limits are applied based on road function and surrounding environment:

- Tempo-30-Zones are typically introduced in residential neighborhoods and side streets. In these zones, priority rules are often modified, meaning intersections generally follow right-before-left regulations rather than established priority roads. Additionally, structural measures such as raised intersections or curb extensions may be implemented to encourage compliance with the lower speed limit (SVI, 2021).
- 30 km/h limits on main roads, such as those introduced through the RNMP, differ in that they apply solely through signage while maintaining existing traffic regulations. Unlike in Tempo-30-Zones, right-of-way rules remain unchanged, meaning priority roads, dedicated lanes, and regulated pedestrian crossings continue to function as before. This ensures that while noise reduction measures are implemented, the fundamental structure and traffic flow of Zurich's main roads remain intact (SVI, 2021).

### Low-Noise Road Surfaces

In areas where speed reductions alone do not meet the desired noise thresholds, according to the RNMP the city uses low-noise road surfaces as an additional measure. These surfaces can reduce noise by up to 3 dB, depending on the material used. The City Council approved the deployment of low-noise road surfaces in April 2022 for approximately 200 kilometers of streets. These upgrades are integrated into routine road construction and resurfacing projects, with full implementation planned by 2040, ensuring cost-effective execution (Stadt Zurich, 2021b).

[1] In German, the term "*Tempo 30*" is commonly used to refer to the "30 km/h speed limit." Both terms are used interchangeably throughout this thesis for consistency and clarity.

### Promotion of Electromobility

In addition electromobility plays an important role in Zurich's long-term road noise mitigation strategy. Electric vehicles generate significantly less noise, especially at low speeds where engine noise dominates. By promoting the transition to electric vehicles and expanding the necessary infrastructure, Zurich aims to fully adopt electromobility by 2050, aligning noise mitigation with broader sustainability goals (Stadt Zurich, 2021a).

### Urban Planning Integration

Furthermore noise mitigation is also incorporated into urban development processes. New buildings in noise-affected areas are optimized during the design and permitting phases to minimize exposure. This involves measures such as orienting noise-sensitive spaces away from busy streets, strategic spatial arrangements (e.g., residential versus commercial uses), and innovative layout designs. These strategies ensure that new developments contribute to a quieter and more livable urban environment (Stadt Zurich, 2022).

### Forecast Road Noise Index

A forecast of the Road Noise Index illustrates how the number of people exposed to noise levels exceeding permissible thresholds (IGW) is expected to decline over time in the City of Zurich with the implementation of the RNMP. The forecast incorporates the planned noise mitigation measures and their combined effects, accounting for synergies with other developments and strategies. The index point for 2022 serves as a reference for the projected improvement curve (Stadt Zurich, 2022).

The Road Noise Index accounts for both the number of people affected by noise exceedances and the severity of those exceedances, with greater weight assigned to higher levels of noise due to their more significant impact on health. The forecast highlights the significant contribution of speed reduction to noise reduction, while emphasizing the need for additional measures such as low-noise road surfaces and electric mobility. A road noise index of zero would indicate that no resident is exposed to excessive road noise at home (Stadt Zurich, 2022). Figure 2.2 illustrates when these measures are planned to be implemented in the future and their projected impact on the road noise index over time.

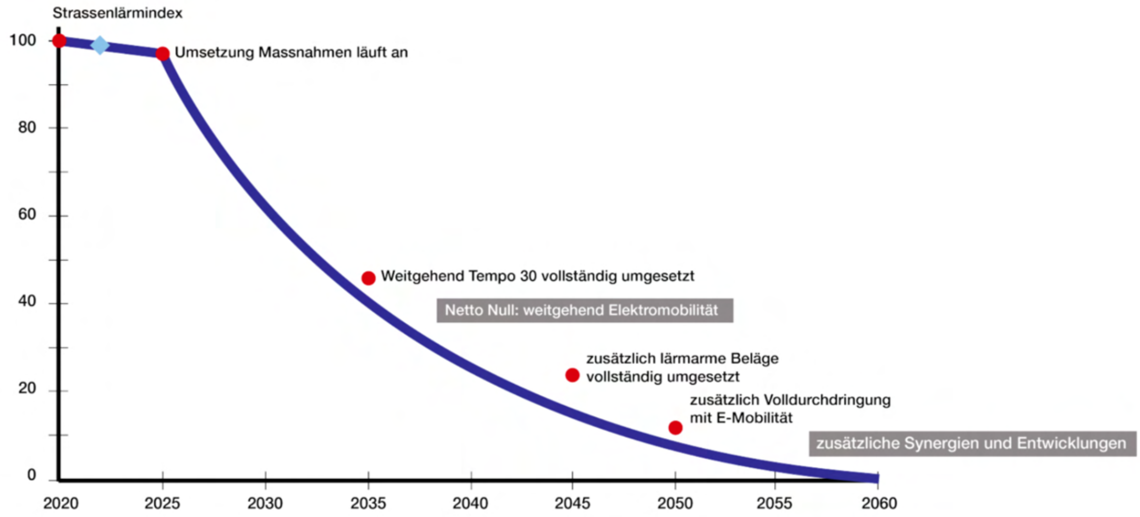



**Figure 2.2:** Predicted Road Noise based on Street Noise Index. The light blue diamonds represent the index values of the respective years. The red points depict the combination of measures including speed reductions, low-noise road surfaces, electromobility, and other synergistic effects (scenarios calculated as of 2020). Since the implementation of these measures will occur simultaneously, the forecast (blue curve) runs below the red points (Stadt Zurich, 2022).

### 2.1.7 Impact of Speed Reductions on Public Transport Travel Times

Speed reductions are widely recognized as an effective measure for mitigating noise pollution, but their implications for public transport operations, particularly travel times, require detailed analysis. A critical factor in this context is the cycle time, which encompasses travel times between stops, dwell times at stations, and turnaround times at terminal stops. Among these, the turnaround time *(German: Wendezeit)* plays a pivotal role in maintaining service reliability and operational efficiency (Verkehrs-Club der Schweiz (VCS), 2023).

Turnaround times fulfill two key functions in public transport operations. First, they act as a buffer to absorb minor delays accumulated during trips, ensuring that the return journey can commence on schedule. Without sufficient buffer time, delays may propagate in both directions, leading to timetable instability and irregular service. Second, turnaround times accommodate essential operational tasks, including driver breaks and staff changes, which frequently occur at terminal stops (Verkehrs-Club der Schweiz (VCS), 2023).

When implementing speed reductions, maintaining adequate turnaround times is crucial to prevent disruptions. Lower speed limits may lead to longer travel times between stops, thereby reducing available turnaround buffers. If these buffers become insufficient, delays can accumulate across multiple trips, affecting overall service reliability. In cases where the impact is substantial, transit agencies may need to introduce additional vehicles or adjust timetables to compensate for the increased travel time (Verkehrs-Club der Schweiz (VCS), 2023).

Thus, ensuring sufficient turnaround times is a key operational consideration when assessing the broader effects of 30 km/h speed limits on public transport efficiency and service continuity. As a result, additional travel time needs cannot simply be compared across different lines without considering turnaround times. These are crucial in determining whether schedule adjustments or the deployment of additional vehicles are necessary to maintain service reliability and operational efficiency Verkehrs-Club der Schweiz (VCS) (2023).

### 2.1.8 Key terminology

#### Traffic Peak Hour

Traffic peak hours *(German: Hauptverkehrszeiten (HVZ))* refer to the times of day with the highest traffic volumes, typically aligning with commuter rush hours. These periods are particularly significant for analysing traffic patterns, noise levels, and the effectiveness of mitigation measures in urban environments. According to the criteria established by VBZ, HVZ occurs only on weekdays, excluding public holidays, and is divided into two distinct periods. The morning peak (HVZ1) spans from 6:30 a.m. to 8:29:59 a.m., corresponding to 23,400 to 30,599 seconds after midnight, while the evening peak (HVZ2) extends from 4:00 p.m. to 6:59:59 p.m., covering 59,400 to 68,399 seconds after midnight.

This thesis focuses specifically on HVZ1 and HVZ2, as discussed with VBZ experts, as these periods capture the most significant traffic flows and associated impacts, making them essential for analysing public transport operations and noise mitigation measures. HVZ1 and HVZ2 are particularly relevant because most vehicles are deployed during these times, and the vehicle fleet is adjusted based on demand during these peak periods.[2] Understanding traffic conditions during these periods is essential for evaluating the performance of the VBZ network .

Since the focus is on HVZ1 and HVZ2, night-time operations (10:00 p.m.–6:00 a.m.) are excluded from this analysis, as they follow different operational patterns and are not the focus of this study. Night-time services typically operate at reduced frequencies, with distinct scheduling strategies that are not directly comparable to daytime peak-hour operations. Consequently, the analysis is centered on the periods with the highest public transport demand and network activity.

#### Independent Rail Bodies (UBK)

Independent rail bodies *(German: Unabhängige Bahnkörper, UBK)* refer to track areas exclusively designated for tram vehicles, separated from road traffic. These include tracks embedded in gravel or grass, providing a dedicated and unobstructed pathway for trams. They are regulated by the Railway Ordinance (*German: Eisenbahnverordnung, EBV*) and represent a distinct type of infrastructure within the Zurich public transport network (Schweizerische Eidgenossenschaft, 2024). Importantly, UBK segments are excluded from speed regulations, such as the introduction of 30 km/h limits, as they operate independently of road traffic and are not subject to the same noise mitigation measures (Baker and Uhler, 2022).

[2] Discussion with VBZ experts during project consultations, February 2024.

### 2.1.9 Accessibility analysis

#### Accessibility in Public Transport Networks

Accessibility is a critical factor in public transport planning, determining how easily residents can reach transit stops and benefit from the service. In Switzerland, the quality of public transport accessibility is often evaluated using the framework of public transport quality classes *German: "ÖV-Güteklassen"*. These classes, defined by the Bundesamt für Raumentwicklung (ARE)[3], assess the quality of public transport systems based on walking distance, service frequency, and overall network coverage (Bundesamt für Raumentwicklung (ARE), 2022).

**Key criteria for public transport quality classes:**

- **Walking distance:** Stops with a walking distance of less than 500 meters are considered highly accessible. In urban areas, walking distances of 300–500 meters are standard for access to high-quality public transport.
- **Service frequency:** High-quality public transport offers frequent departures. For example, main lines with a frequency of 10 minutes or less during peak hours are rated as highly accessible.
- **Network coverage:** A well-connected network ensures that the majority of the population has access to stops within a short walking distance, without significant service gaps (Bundesamt für Raumentwicklung (ARE), 2022).

These criteria are particularly relevant in dense urban environments such as Zurich, where public transport is a main mode of mobility. Ensuring compliance with these standards is crucial for maintaining the effectiveness and usability of public transport systems.

The consolidation or reduction of stops must be carefully evaluated within the framework of public transport quality classes to ensure that walking distances remain within acceptable limits and that service quality is not compromised. For instance, the ARE methodology suggests that increasing the average distance between stops could negatively impact the transport quality classes rating in densely populated areas (Bundesamt für Raumentwicklung (ARE), 2022).

#### Distance from Residential Areas to Stops

The distance residents must walk to reach a public transport stop significantly influences the likelihood of public transport usage. Exceeding acceptable walking distances, typically between 400 and 600 meters in urban areas, can discourage potential users, particularly those with limited mobility or other restrictions (Bundesamt für Raumentwicklung (ARE), 2022).

In Zurich, the distribution of public transport stops ensures high accessibility, with most stops spaced approximately 300 to 400 meters apart. This strategic placement supports the high public transport ridership of the city, with 860,000 passengers daily on the VBZ network (Verkehrsbetriebe Zurich, 2023).

[3] The Bundesamt für Raumentwicklung (ARE) is the Swiss Federal Office for Spatial Development, responsible for sustainable spatial and transport planning, including the coordination of transport, environmental, and land use policies in Switzerland.

Stops with distances of less than 300 meters between them have frequently been identified for possible consolidation by VBZ experts. The goal of such measures is to create a single, strategically placed stop that optimizes travel time by reducing the number of stops vehicles must make. However, these adjustments often face political challenges, as they require careful consideration of public acceptance and accessibility impacts. Balancing these factors is critical to ensuring that any stop relocation maintains high levels of accessibility while improving overall travel time [4].

On the other hand, fewer stops can also lead to time savings for passengers already on board, as overall travel times decrease due to fewer interruptions. This effect can enhance the efficiency of public transport, particularly on high-frequency routes where excessive stopping negatively impacts service reliability [5]. These competing factors highlight the importance of accessibility analysis to fully understand the potential impacts of stop adjustments on public transport users (Verkehrs-Club der Schweiz (VCS), 2023).

Given these considerations, the stops *Löwenbräu* and *Quellenstrasse*, which are separated by only about 200 meters, serve as an ideal case study to further analyse the effects of stop removal and consolidation on passenger walking times.

## 2.2 Literature Review

### 2.2.1 Impact of 30 km/h Speed Limits on Travel Time

Numerous studies have examined the impact of introducing 30 km/h speed limits on public transport travel times, with a particular focus on buses. These studies provide a range of estimates for the additional time required per 100-meter segments. Table 2.2 summarizes the findings, indicating an average additional time of 1.5 seconds per 100 meters with a standard deviation of 0.6 seconds.

An analysis conducted by VBZ evaluated the impact of 30 km/h speed limits on specific street segments in Zurich. The findings revealed that time losses for public transport vehicles ranged from 1 to 3 seconds per 100 meters, comparable to those for private vehicles (VBZ, 2019). Similarly, the Verkehrs-Club der Schweiz (VCS) reported an average additional time of 1.5 seconds per 100 meters during peak hours, attributing the limited impact to high traffic volumes that naturally constrain vehicle speeds (Verkehrs-Club der Schweiz (VCS), 2023).

Further studies highlight variations in additional travel times depending on factors such as topography, traffic density, and signalization. Metron (1994) and Eckart (2018) consolidated empirical measurements, estimating travel time increases of 0.4 to 2.7 seconds per 100 meters. For example, on steep inclines or highly congested routes, additional travel time was as low as 0.4 seconds per 100 meters, while flatter or less congested sections showed higher increases of up to 1.6 seconds (Metron, 1994; Eckart et al., 2018).

[4] Discussion with VBZ experts during project consultations, February 2024.
[5] Discussion with VBZ experts, January 2025.

| Additional Time Needed per 100m/s | Description | Source |
|---|---|---|
| 1.2 | Average across different lines | (VBZ, 2019) |
| 0.4 | Uphill direction | (Metron, 1994) |
| 1.6 | Downhill direction | (Metron, 1994) |
| 1.1 | From: Dittmann 2013 | (Eckart et al., 2018) |
| 1.4 | From: Bruckner 2017 | (Eckart et al., 2018) |
| 2.0 | From: City of Zurich 2010 | (Eckart et al., 2018) |
| 2.7 | From: Bruder et al. 1989 | (Eckart et al., 2018) |
| 1.8 | From: Birk et al. 1993 | (Eckart et al., 2018) |
| **1.5** | **Average** | |
| **0.6** | **Standard deviation** | |

**Table 2.2:** Additional time needed per 100m/s based on various studies (Verkehrs-Club der Schweiz (VCS), 2023).

Case studies in Stuttgart and Lucerne further confirm these findings. Dittmann (2013) simulated the introduction of a 30 km/h speed limit on a 2.3 km bus route in Stuttgart, reporting an increase in travel time of 21 seconds (1.1s per 100m). The most significant delays occurred on sections with fewer stops, highlighting the amplified impact of speed reductions on longer, uninterrupted segments. Similarly, an evaluation in Lucerne noted average travel time increases of 4 seconds per stop, with maximum delays of up to 35 seconds on extended routes. Interestingly, the implementation of *Tempo 30* on traffic-oriented streets like Bernstrasse and Udligenswilerstrasse showed no measurable effects on bus operations (Dittmann, 2013; Kanton Luzern, 2024).

According to SVI (2021) and Eckart et al. (2018) the effective additional time for bus lines under 30 km/h speed limits is estimated to range between 0.9 and 2.1 seconds per 100 meters, with an average of 1.5 seconds (SVI, 2021; Eckart et al., 2018). Although the additional travel time is generally negligible for shorter segments, it becomes more pronounced on longer stretches. These findings underscore the importance of individually evaluating affected routes and implementing complementary measures, such as optimized traffic signal timings, to mitigate operational inefficiencies (Verkehrs-Club der Schweiz (VCS), 2023).

Jang et al. (2022) provided further insights using traffic simulations under various conditions. The study demonstrated that in congested urban areas, 30 km/h speed limits have minimal effects on travel times since vehicles already struggle to reach maximum speeds. Conversely, in low-density areas with fewer obstacles, speed reductions have a more noticeable impact, particularly for public transport systems with long-distance segments (Jang et al., 2022).

### 2.2.2 Accessibility and stop optimization in public transport networks

In the context of this thesis, the consolidation or removal of transit stops is considered a potential measure to compensate for the travel time losses caused by the introduction of *Tempo 30*. However, it is important to note that Zurich has a very high density of transit stops. Removal or consolidation discussed would not compromise the overall accessibility of the public transport network but may result in longer walking distances for a portion of users. This underscores the need for careful evaluation of the trade-offs between operational efficiency and equitable access.

Increasing the distance between stops can improve transit efficiency by reducing the frequency of deceleration, acceleration, and passenger boarding and alighting. However, removing stops reduces the accessibility of public transport, especially in densely populated areas where proximity to stops is critical for usability. Additionally, stop removals often face strong public resistance, limiting the practical application of such measures. As a result, increasing the distance between stops is rarely implemented in practice (Verkehrs-Club der Schweiz (VCS), 2023; SVI, 2013).

Accessibility is a critical metric for evaluating the performance of public transport systems. The proximity of transit stops to residential areas significantly influences public transport usage, as longer walking distances can discourage potential users. This trade-off between improved travel speed and reduced accessibility highlights the complexity of optimizing stop locations. While the removal or consolidation of stops can enhance operational efficiency, it risks diminishing the reach and usability of public transport services, particularly in urban areas where comprehensive coverage is essential to maintaining high ridership levels. These considerations underscore the importance of carefully analysing accessibility when proposing changes to public transport stop configurations (Verkehrs-Club der Schweiz (VCS), 2023; SVI, 2013).

Kharel et al. (2019) utilized GIS-based network analysis to optimize bus stop locations in Bengaluru, taking into account factors such as traffic signals, accessibility, and travel demand. Their findings emphasize the importance of balancing stop density to ensure both operational efficiency and equitable access. Similarly, Lao and Liu (2009) integrated GIS with Data Envelopment Analysis (DEA) to evaluate bus line performance, incorporating demographic profiles and operational metrics. This comprehensive approach highlights the trade-offs between spatial accessibility and operational efficiency (Kharel et al., 2019; Lao and Liu, 2009).

The study by Albacete et al. (2017) compared different methodologies for assessing public transport accessibility, demonstrating that results can vary significantly depending on the tools and data used. Their findings underscore the importance of selecting an appropriate evaluation approach, particularly when analysing the trade-offs between accessibility and operational efficiency in the context of speed reductions and stop optimizations (Albacete et al., 2017). Similarly, Tenkanen et al. (2016) highlighted the dynamic nature of accessibility, which fluctuates based on time of day and transport mode, further emphasizing the need for context-specific analysis in densely populated cities like Zurich (Tenkanen et al., 2016).

To account for the distinct characteristics of Zurich's public transport network, the methodology for this thesis was developed in close collaboration with VBZ experts, ensuring that the analysis accurately reflects the city's operational conditions and planning objectives.

### 2.2.3 Research Gaps

The relationship between speed reductions and their effects on travel times is a critical aspect of urban transport planning, particularly within the framework of Zurich's RNMP. analysing strategies to optimize public transport operations under the constraints of reduced speed limits is essential to preserve attractive travel times while maintaining a high quality of accessibility. A review of the existing literature on the impacts of speed reductions—especially their influence on public transport reveals several important gaps that warrant further exploration. Specifically, four prominent gaps have been identified:

**1. 30 km/h speed limits impact on entire public transport network:** There is a lack of research that specifically examines how Zurich's RNMP affect the entire public transport network. This includes changes in the average speeds and median travel times of public transport. Additionally, VBZ, Zurich's public transport operator, has noted that the network-wide impacts of 30 km/h speed limits on operational performance remain uncertain, emphasizing the need for detailed analysis.

**2. Segment-level analysis in urban public transport:** Existing studies rarely consider the granular impact of speed reductions on public transport systems at the segment level. The lack of research utilizing 20-meter segments to evaluate traffic highlights an opportunity for a more detailed, data-driven analysis of speed reductions on specific tram and bus routes, providing a deeper understanding of localized operational impacts.

**3. Effects of speed reductions on tram operations:** Most studies focus on the impact of speed reductions on buses, which operate in mixed traffic and are more susceptible to congestion. However, the effects on trams, many of which run on UBK, remain underexplored. It is unclear whether speed reductions have a significant effect on tram travel times or if their operational characteristics mitigate potential delays. Understanding these differences is essential for developing targeted mitigation strategies.

**4. Impact of stop adjustments on accessibility and efficiency:** While stop removal or consolidation is often proposed as a strategy to counterbalance travel time increases, limited research has examined how these measures affect accessibility—particularly in cities with dense public transport networks like Zurich. Macro-level studies provide general insights, but a detailed analysis of how stop adjustments influence passenger walking distances and accessibility is needed.

Consequently, this thesis aims to address these gaps by providing a comprehensive and nuanced understanding of the impacts of speed reductions and their implications for public transport operations.

### 2.2.4 Research Objectives

Building on the identified research gaps, this study aims to achieve the following goals:

**Research Objective 1: Assessing the impact of Zurich's RNMP on public transport travel times** The objective evaluates how the third phase of Zurich's RNMP—which includes the implementation of 30 km/h speed limits—affects travel times for trams and buses across the network. The speed regimes and travel times under the RNMP are compared with the reference period from April and May 2023, which serves as the pre-implementation baseline. The analysis considers variations between transport mode (tram or bus), direction 1 and 2, and time of day, specifically focusing on HVZ1 and HVZ2. The study aims to quantify additional travel time needs, identify their locations, and evaluate variations throughout the network, while also pinpointing individual lines that are most significantly affected under these conditions.

**Research Objective 2: Analysing the effects of stop adjustments on accessibility.** This research objective evaluates the effects of stop removal or relocation, focusing on how increased distances between public transport stops influence accessibility. A detailed case study is conducted for the stops *Löwenbräu* and *Quellenstrasse*, assessing the impact on walking distances for residents and exploring the potential benefits for public transport travel times. These adjustments are considered in the context of this study as a possible measure to compensate for travel time losses caused by the implementation of the 30 km/h speed limit, balancing network efficiency with accessibility for the affected population. Four scenarios are analysed to evaluate different approaches to stop consolidation and their respective impacts on accessibility.

# Chapter 3

# Data

This Chapter provides a comprehensive overview of the data sets used in this thesis and their integration to form the basis for the analysis. The subsequent sections provide a detailed explanation of each data set.The combination of the following data sets enables the analysis of the effects of the RNMP and accessibility analysis:

| **Attribute** | **Details** |
|---|---|
| Vehicle events | GPS coordinates, odometer readings, date, timestamps, and speed data. |
| Stop events | Stop IDs, route numbers, trip IDs, and actual arrival/departure times. |
| Calendar data | Weekday classification and public holiday indicators. |
| Vehicle type data | Vehicle classification and technical identifiers. |
| RNMP data | Road Noise Mitigation Plan measures and affected segments. |
| UBK | Tracks exclusively used by trams. |
| Accessibility features | Pedestrian network, building entrances, and transit stops. |
| Visualization data | Rivers, lakes, green spaces, city boundaries, and building footprints. |

**Table 3.1:** Overview of Data Attributes.

## 3.1 Effects of the RNMP

### 3.1.1 Vehicle Event Data

The vehicle event data[1] consist of detailed information on public transport vehicles operating in Zurich, measured in GPS points. This data is collected continuously along route segments between public transport stops. The dataset captures geographical, temporal, and speed-related information, serving as a foundational element for analysing public transport operations and assessing traffic flow. An example of raw vehicle data can be seen in Figure 3.1.

Position data for each vehicle event is recorded every 10 seconds across the network, capturing key event types such as the start and end of trips and the exact time when doors open or close (recorded when the driver activates the door button). However, the dataset does not include stop segment information, bus/tram line identifiers, or full route details. As described in Section 3.1.2, stop event data provide the missing node-related information, which is later integrated with the vehicle event data for a comprehensive analysis.

For this study, GPS positioning was chosen over odometer-based tracking due to its high spatial accuracy and direct measurement of vehicle positions. GPS data provides absolute positioning, making it suitable for public transport analyses, especially in studies focusing on travel times, speed variations, and route-based assessments as done in Mazloumi et al. (2009) and Chawuthai et al. (2023). This method aligns with standard practices in public transport research, where GPS data is widely used for spatial analysis and performance evaluations.

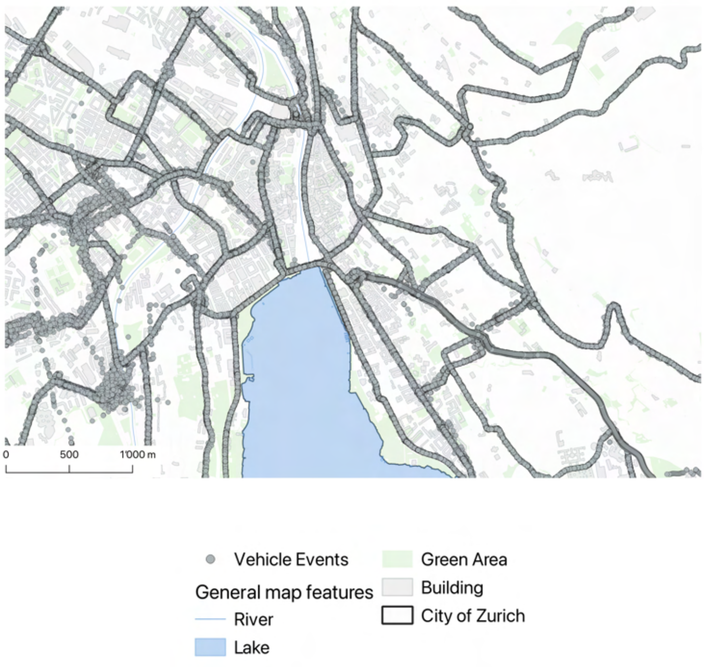



**Figure 3.1:** Example of raw vehicle event data during HVZ1 in direction 1, including trips to the depot, which were excluded from the analysis, see Methodology Section 4.2.1

[1]The vehicle event data were provided by VBZ, which is not available to the public.

### 3.1.2 Stop Events

The data of stop events[2] are essential to accurately map public transport stops within the Zurich transport network. While vehicle event data capture continuous movement along route segments, stop event data provide node-based insights, including unique stop identification numbers (IDs), arrival and departure times, and dwell times. These details enable a precise temporal and spatial representation of operations at each stop.

Stop events serve as fixed reference points within the network, which are crucial for integrating route-based vehicle event data. By linking the two data sets through shared IDs, a cohesive data set is formed, combining the spatial and temporal attributes of vehicle movements in relation to stops.

This connection between vehicle events and stop events is critical for evaluating the impact of proposed interventions, such as changes in speed regimes. By examining the linkage, it is possible to determine whether a vehicle event occurred between two stop nodes or specifically at a stop. When the stop ID at both ends of a segment matches, it confirms that the vehicle event was recorded at a stop node, facilitating a comprehensive understanding of the network's performance.

### 3.1.3 Calendar Data

To provide a temporal framework for the vehicle and stop event data, these datasets were linked with calendar data[3]. This linkage was established by matching stop event and vehicle event IDs with the calendar dataset, enabling the integration of key temporal attributes such as the day of the week and holiday status.

The incorporation of calendar data was essential for filtering the dataset to align with the reference period, spanning from April 1, 2023, to May 31, 2023. This period was selected as it represents typical network conditions, serving as a reliable baseline for assessing the impacts of the RNMP[4]. Additionally, the calendar data were used to classify the dataset into HVZ1 and HVZ2, which are further detailed in Section 2.1.8 *Key Terminology.*

### 3.1.4 Vehicle type data

The vehicle type data set [5] used for this analysis contains detailed information about the vehicles operating on the public transport network in Zurich. This data set includes attributes such as vehicle identifiers and descriptions, which are essential for distinguishing between trams and buses.

The vehicle type data set, in combination with the vehicle event data from Section 3.1.1, stop event data from Section 3.1.2, and calendar data from Section 3.1.3, forms the foundation for the subsequent analysis of public transport performance and the assessment of noise mitigation measures implemented on the network.

[2]The stop event data were provided by VBZ, which are not available to the public.
[3]The vehicle data were provided by VBZ and are not publicly available.
[4]Discussion with VBZ experts during project consultations, February 2024.
[5]The vehicle type data were provided by VBZ, which are not available to the public.

### 3.1.5 Road Noise Mitigation Plan

The data set with information about the third phase of the RNMP [6] was sourced from the City of Zurich Open Government Data platform. It was provided as a shapefile and last updated on December 2, 2021. It specifies planned speed limits for individual street segments and highlights areas where further measures need to be implemented. Thereby eight possible implementation for steet segments are possible that are further explained in 3.2. As shown in Figure 3.2, the data set provides a spatially explicit representation of Zurich's street network, categorizing segments based on their future tempo regime.

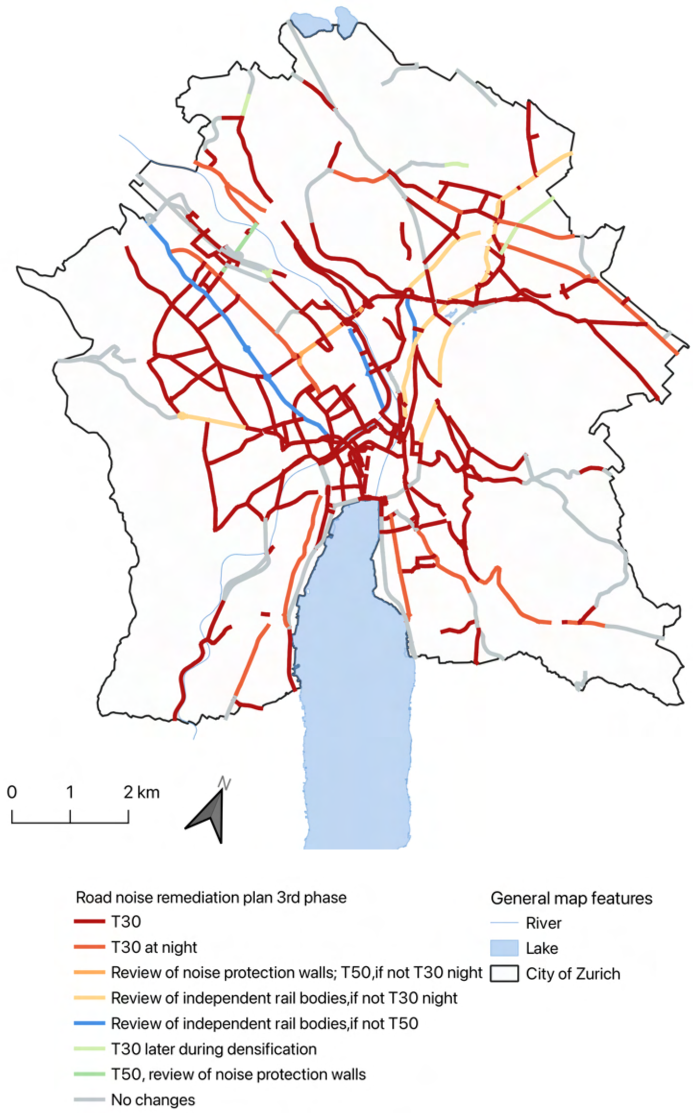



**Figure 3.2:** Road Noise Mitigation Plan

For this study, the analysis focuses exclusively on the impacts of the 30 km/h speed limits (*T30*) on tram and bus lines. Sections with night-time speed limits [7] (*T30 at night* were excluded from the analysis, since the focus is on HVZ1 and HVZ2. Furthermore, other categories

[6] https://data.stadt-zuerich.ch/dataset/geo_strassenlaermsanierung
[7] Night is defined between 10:00 pm. to 6:00 am

within the data set, such as segments requiring further deliberations or additional measures like noise protection walls or review of independent rail bodies, were not included, as these require additional clarification and are beyond the scope of this thesis.

| Category | Explanation |
|---|---|
| T30 | A 30 km/h speed limit applies day and night. |
| T30 at night | A 30 km/h speed limit applies during nighttime to reduce road noise. |
| Review of noise protection walls; T50 if not T30 night | Noise protection walls are assessed. If feasible, a 50 km/h limit applies; otherwise, T30 at night. |
| Review of UBK; if not T30 night | UBK feasibility is evaluated; if not possible, T30 at night applies. |
| Review of UBK; if not T50 | UBK feasibility is evaluated; if not possible, T50 applies. |
| T30 later during densification | The 30 km/h speed limit is applied later as densification progresses. |
| T50, review of noise protection walls | A 50 km/h limit applies while assessing the need for noise protection walls. |
| No changes | The existing speed regime remains unchanged. |

**Table 3.2:** Categories and explanations of the Road Noise Mitigation Plan (3rd Phase), including speed limits and noise reduction measures.

### 3.1.6 Independent Rail Bodies (UBK)

As outlined in the Key terminology in Section 2.1.8, UBK are exempt from speed regulations, making them a critical component when analysing speed regimes and their impact on tram travel times. To account for this, the UBK dataset provided as a shapefile was integrated into the analysis to accurately reflect segments unaffected by the 30 km/h speed limits.

However, as illustrated in Figure 3.2, certain segments are currently under review to determine whether they meet the criteria for UBK classification (see Table 3.2). For these segments, this study adopts a restrictive approach, assuming that UBK classification will not be granted and that speed reductions will apply. This decision reflects the uncertainty surrounding the formal review process and the complexities involved in securing UBK status, as emphasized during consultations with VBZ experts.[8]

For the purposes of this analysis, only segments that are officially classified as UBK were included. Figure 3.3 provides an overview of Zurich's officially designated UBK segments, which form the basis for this study. The UBK data were provided by VBZ and are not publicly available.[9]

[8]Discussions with VBZ experts during project consultations, February 2024.
[9]UBK data provided by VBZ for the purposes of this study.

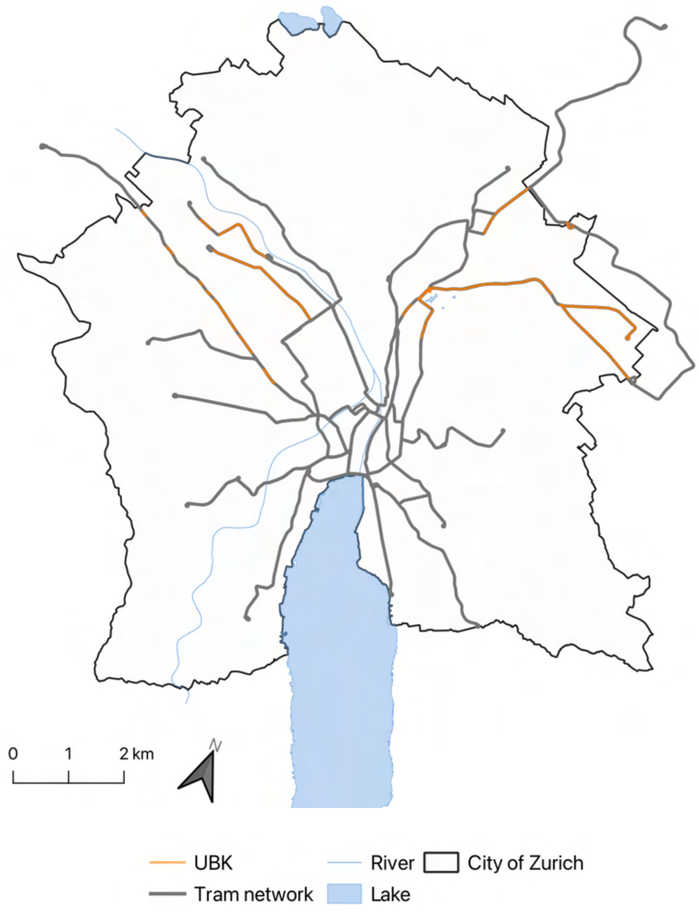



**Figure 3.3:** Overview of tram network with UBK in Zurich

## 3.2 Accessibility analysis

### 3.2.1 Pedestrian Network

The pedestrian and cycling network data set [10] includes all pedestrian and cycling paths within the City of Zurich and serves as the foundation for the city's routing planner.

For the purposes of the accessibility calculations in this thesis, only the pedestrian network from the provided shapefile was utilized. The cycling network was explicitly excluded to ensure a focus on pedestrian paths and to maintain the accuracy of the analysis for walking distances to public transport stops. as can be seen in Figure 3.4 the data set contains deailed information on Pedestrian-accessible paths, such as sidewalks, pedestrian crossings, and footbridges.

[10] https://data.stadt-zuerich.ch/dataset/geo_fuss__und_velowegnetz


**Figure 3.4:** Example of detailed pedestrian network grid

### 3.2.2 Building Entrances

The data set of apartment entrances provides up-to-date, georeferenced building entrances within the City of Zurich, based on the building and housing register *(German: Gebäude- und Wohnungsregister (GWR))* data model. [11]

The GWR of the City of Zurich, maintained by the Statistics Office of the City of Zurich, serves as the foundation for legally mandated data submissions to the Swiss Federal Statistical Office, which oversees the GWR. The GWR contains essential baseline information on buildings and apartments across Switzerland. It is widely utilized for statistical research, and planning purposes and supports cantons and municipalities in fulfilling legal obligations.

For this thesis, the building entrances were used as a key input for accessibility analyses. By linking apartment entrances to pedestrian networks, the accessibility of public transport stops for residents of Zurich could be evaluated.

[11] `https://data.stadt-zuerich.ch/data-set/geo_gebaeude_und_wohnungsregister_der_stadt_zuerich__gwz__gemaess_gwr_datenmodell`

### 3.2.3 Public Transport Stops

The data set for public transport stops[12] contains detailed georeferenced information on all tram stops, bus stops, and other public transport stops within the canton of Zurich. For this analysis, the data was filtered within the city boundaries and the VBZ network. The data set includes key attributes such as stop IDs, names, locations, and the transport modes served at each stop.

In this thesis, the dataset was utilized to map the spatial distribution of public transport stops across Zurich, facilitating better orientation within the network and identifying the specific segments affected by changes. Additionally, it was used to assess accessibility to public transport stops for residents by incorporating apartment entrance locations and pedestrian networks.

## 3.3 Data for Visualization

For the map creation and visualization, multiple data sets from the City of Zurich's Open Government Data Catalog [13] were used to provide a detailed spatial context for the analysis. These data sets included:

- **City boundaries:** Provides the administrative boundaries of Zurich.[14]
- **City districts:** Represents the larger administrative divisions of Zurich.[15]
- **Standing and flowing water bodies:** Includes detailed geometries of rivers, lakes, and other water bodies within Zurich.[16]
- **Green spaces:** Covers parks, forests, and other green areas in the city.[17]
- **Building footprints:** Contains accurate geospatial information on all building outlines within the city.[18]

[12] https://data.stadt-zuerich.ch/dataset/ktzh_haltestellen_des_oeffentlichen_verkehrs___ogd_
[13] https://data.stadt-zuerich.ch/
[14] https://data.stadt-zuerich.ch/dataset/ktzh_gemeindegrenzen__ogd_
[15] https://data.stadt-zuerich.ch/dataset/geo_stadtkreise
[16] https://data.stadt-zuerich.ch/dataset/ktzh_av_gewaesser__ogd_
[17] https://data.stadt-zuerich.ch/dataset/geo_gruenflaechen
[18] https://www.stadt-zuerich.ch/geodaten/download/Gebaeude_verkippt

# Chapter 4

# Methodology

This Chapter outlines the technical setup, data preparation, and analytical methodologies employed in this study. The methodologies applied were developed in close collaboration with Verkehrsbetriebe Zürich (VBZ) to account for the unique operational characteristics of Zurich's public transport network. The Chapter is divided into two main sections:

Section 4.2: Presents the methodology for analysing the impact of the Road Noise Mitigation Plan (RNMP) on public transport operations. This includes assessing speed regime changes and their influence on travel times, generating insights that directly support VBZ's planning and operational strategies.

Section 5.2: Details the approach used to evaluate the accessibility impacts of stop modifications, focusing on the transit stops *Löwenbräu* and *Quellenstrasse*. The analysis considers four distinct scenarios to assess changes in walking distances and accessibility resulting from stop removal or consolidation.

## 4.1 Technical Setup

To comply with VBZ security requirements, all computational steps involving disaggregated data were performed on a HP EliteBook x360 1030 G4. Thereby, Databricks endpoint configured with 4 DBU/h (2X-Small) was used to access the data. The analysis was conducted using R software (version 4.3.2) and RStudio (version 2024.04.01), accessed via a Posit workbench, which was configured to support up to 8 CPUs and 60 GB of RAM. This setup ensured that both exploratory and computationally intensive tasks could be performed efficiently.

The aggregated data were transferred to a MacBook Air running macOS Sonoma 14.5. This device, equipped with 8 GB RAM and a 3.2 GHz 8-core CPU, was used for additional analysis and visualization. R version 4.4.2 and RStudio version 2024.12.0+467 were employed for further data processing, and the utilized R packages are listed in the Appendix D. Advanced mapping and geospatial analyses were conducted using QGIS version 3.38.3 'Grenoble,' leveraging its robust geospatial processing and visualization capabilities.

This technical setup was designed to ensure compliance with VBZ's data protection policies, while enabling efficient processing of large datasets and robust statistical and geospatial analyses.

## 4.2 Effects of RNMP

### 4.2.1 Preprocessing Data

#### Spatial Data Transformation

The geospatial data sets were reprojected from the VBZ custom coordinate system to WGS84 (EPSG: 4326), and later to the Swiss standard LV95 (EPSG: 2056) coordinate system. The transformation process was carried out using the `sf` package in R[1].

#### Data classification

The four primary data sets—vehicle events, stop events, vehicle type, and calendar data—were integrated using SQL queries, linking them through unique identifiers. Vehicle and stop events were matched to associate each recorded vehicle movement with its corresponding stop event, while calendar data enabled precise filtering by date and time. Additionally, the vehicle type data set was used to differentiate between VBZ-operated trams and buses. This integration provided a comprehensive representation of public transport operations, combining spatial, temporal, and operational attributes.

**Classification into HVZ1 and HVZ2** To analyse public transport performance during peak periods, the vehicle events were categorized into HVZ1 and HVZ2 based on their timestamps. HVZ1 includes all vehicle events recorded between 06:30 and 08:29:59, while HVZ2 (evening peak hour) covers events between 16:00 and 18:59:59. This classification was implemented by extracting vehicle event timestamps and matching them with predefined HVZ time windows, ensuring that only trips occurring during peak traffic conditions were included. Weekends

[1] `https://cran.r-project.org/web/packages/sf/index.html`

and public holidays were also further excluded, as they do not align with regular peak-hour commuting patterns.

**Direction Classification and Filtering** To facilitate analysis and visualization, vehicle events were categorized into two travel directions: Direction 1 (outbound journey) and Direction 2 (return journey). This classification was primarily chosen to enhance visualization clarity in later map representations. Without distinguishing travel directions, overlapping trajectories of opposing movements would obscure spatial trends and patterns in the segment-based analysis.

#### Integration and Quality Assurance

To ensure the reliability and consistency of the data set, quality assurance measures were applied throughout the integration process:

- **Exclusion of implausible data:** Events with unrealistically high speeds exceeding 65 km/h were removed, as such values are improbable within Zurich's urban public transport network.
- **Handling of missing or infinite values:** Records with missing or infinite values in key attributes were excluded to maintain data integrity and analytical accuracy.
- **Exclusion of depot trips:** Trips to and from depots were removed from the analysis using a nearest-neighbor approach, matching vehicle events to the created 20-meter segments (as detailed in Section 4.2.4). This step ensured that only operational trips during HVZ1 and HVZ2 were considered, preventing non-representative data from affecting the results.

#### Adjustments for Stationary Periods

Events with a recorded speed of 0 km/h were adjusted to a minimal non-zero value of 0.000001 km/h. This decision was made after evaluating various approaches in consultation with VBZ experts[2]. The adjustment ensures that stationary periods—such as vehicles waiting at traffic signals, or halted in traffic congestion—are adequately represented in the analysis. Notably, public transport vehicles often experience standstill periods away from designated stops due to congestion or operational delays.

By incorporating these stationary events, the analysis provides a more accurate representation of real-world public transport operations, particularly during peak traffic hours. This approach prevents unintended data and ensures that variations in travel time caused by traffic flow, signal delays, and stop durations are fully captured in the study.

### 4.2.2 Exploratory Analysis

The initial exploratory phase of this study involved a comprehensive examination of various aspects of the public transport network, with a particular focus on the impact of speed limits implemented to mitigate road noise. Simple visualizations were employed to quantify the extent to which specific tram and bus lines are affected by the 30 km/h speed limits. These visualizations also provided first insights into the overall coverage of the network subject to the new speed

[2] Discussion with VBZ experts during project consultations, February 2024

limits introduced by the RNMP.

Additionally, the exploratory phase included an analysis of the planned modifications under the RNMP, such as the locations and scope of these changes throughout the network. These modifications were mapped to understand their spatial distribution and identify areas that would experience reduced speed limits.

Using R and QGIS, maps and graphs were created to visualize the road network, highlighting areas affected by the 30 km/h speed regulation. In this early stage, the focus was primarily on the spatial distribution of these changes, providing a foundational understanding of the affected areas. This analysis laid the groundwork for more detailed investigations into the impacts of these changes on public transport performance.

### 4.2.3 Speed Calculation and Distance Measurement

The distance between consecutive vehicle events was computed in meters using the LV95 coordinate system, allowing for precise spatial measurements. The corresponding speeds were derived in meters per second (m/s) and kilometers per hour (km/h) using the Formula 4.1 and Formula 4.2:

$$\text{Speed} = \frac{\text{Distance}}{\text{Time}} \tag{4.1}$$

Where: - Distance is the straight-line distance between consecutive vehicle events, - Time is the time difference between the events (in seconds).

To convert the speed to kilometers per hour, the following formula was used:

$$\text{Speed (km/h)} = \text{Speed (m/s)} \times 3.6 \tag{4.2}$$

### 4.2.4 Segmentation and Analysis

For this analysis, three spatial dimensions were considered in different contexts:

- **20-meter segments:** Detailed analysis of speed and travel time changes.
- **Each tram and bus line separately:** Enables route-specific assessments, identifying localized impacts and variations between different lines.
- **Entire tram and bus network:** Provides a comprehensive overview of network-wide impacts, primarily represented in tables.

The 20-meter segment unit was initially selected because it had previously been used in VBZ methodologies (VBZ, 2019). This choice was reaffirmed through discussions with VBZ experts[3], who confirmed its effectiveness in analysing changes to speed regimes in past studies. An additional reason for selecting 20-meter segments is their ability to provide high resolution,

[3] Discussion with VBZ experts during project consultations, February 2024

allowing investigation of localized impacts of the RNMP. This granularity is particularly useful for capturing detailed changes in speed and travel time, making it ideal for this level of analysis.

analysing each tram and bus line separately enables a more precise evaluation of how individual routes are affected by the RNMP. Since different lines operate in varying urban contexts—such as dedicated tram tracks versus mixed-traffic lanes—the impact of speed reductions or regulatory changes can vary significantly. Evaluating each line individually allows for a more targeted interpretation of the results. Additionally, considering each line separately is crucial for assessing turnaround times, as delays on one end of a route can impact subsequent departures and overall schedule stability.

On the other hand, considering the entire tram and bus network provides a broader perspective, highlighting the overall trends and cumulative effects of the RNMP. This approach is particularly useful for identifying systemic patterns, understanding network-wide delays, and ensuring that findings are not limited to isolated segments but reflect the general impact across Zurich's public transport system.

#### Integration of vehicle data to segments

To spatially integrate vehicle event data with the 20-meter segments, a nearest neighbor analysis was applied (QGIS, 2025; Dabo and Yunus, 2020). This method assigned each recorded vehicle position to the closest corresponding segment, ensuring a precise spatial representation of public transport movements. A threshold of 5 meters was set to limit assignment errors and to exclude trips to and from depots, as these movements are not part of the regular operations during peak hours and are therefore outside the study's scope.

The segmentation was structured by direction, meaning vehicle events were mapped separately to Direction 1 (outbound) and Direction 2 (return journey). This approach ensured that the spatial matching process reflected the bidirectional nature of the network, allowing for a more granular analysis of travel time impacts.

Given that GPS data can contain inaccuracies due to signal propagation errors, atmospheric conditions, and receiver limitations, a systematic approach was implemented to filter out erroneous GPS points. The nearest neighbor method played a key role in excluding misclassified GPS positions that did not correspond to the expected network trajectory. According to Suda (2017), such positional deviations are common in urban environments and can affect spatial analyses if not properly accounted for. By applying nearest neighbor matching with a strict distance threshold, vehicle events that were erroneously located off the actual transport routes were automatically excluded.

### 4.2.5 Statistical Analysis

For each 20-meter segment, statistical measures were calculated to analyse the speed in the reference period. The calculated metrics included:

- **Basic Statistics:** Count, minimum, maximum, range, and sum.
- **Central Tendency and Variability:** Mean, median, and standard deviation.
- **Distribution Metrics:** Quartiles (Q1, Q3) and interquartile range (IQR).

The focus was especially on the median and Q3 (third quartile) were calculated to provide a robust representation of the central tendency and spread of the data. The median divides the data set into two equal halves, with 50% of the data points falling below and 50% above. Q3 represents the value below which 75% of the data points fall, and 25% of the data points are above. These measures were specifically focused on to reduce the influence of outliers and to provide insights into the overall performance of the network.

These metrics were computed for each segment individually, providing a detailed statistical profile for every section of the network. This approach ensured that both local variations in speed and travel time—within individual segments and between transit stop segments—were accurately captured and analysed. The results provide a robust foundation for evaluating the impact of the RNMP on the performance of Zurich's public transport system.

### 4.2.6 Integration of the RNMP and UBK

The integration of the RNMP into the analysis was based on a shapefile provided by the City of Zurich, detailing the designated 30 km/h speed limits. This shapefile was combined with the UBK shapefile. Since trams operating on UBK tracks are exempt from the new speed regulations, these segments were excluded from speed reductions.

To align the RNMP and UBK data with the preprocessed 20-meter segments, a nearest-neighbor method with a distance threshold of five meters was implemented in QGIS (QGIS, 2025; Dabo and Yunus, 2020). This approach ensured that each segment was assigned the correct speed regime while accounting for direction-specific information, which was not explicitly provided in the original RNMP shapefile. The method accurately linked speed regulations to both Direction 1 and Direction 2 segments, ensuring that speed limits were correctly applied in the analysis.

As illustrated in Figure 4.1, minor GPS deviations from the centerlines of the segment required this spatial matching technique to ensure precise alignment. This integration linked the movement data to their respective segments, incorporating the updated speed regulations.


**Figure 4.1:** Example of GPS points for vehicle events in HVZ1 direction 1 across the Bus Network (Bus line 64 and 75)

### Speed Values with RNMP and Methodological Considerations

As discussed in Section 3.1.6, a restrictive approach was adopted, which means that only existing UBK segments were classified as independent tracks, while segments still under review were not considered exempt from speed reductions. This assumption ensures a conservative estimate of travel time changes under the RNMP.

Now the segments had the information about the speeds of the reference period, as well as the new speed regime which will follow under the RNMP. Thereby the following speed values were applied in the analysis in order to calculate the expected speed caused by the RNMP:

- **Tram Segments:**
  - If the segment was located within an existing UBK, the original median speed from the reference period was retained.
  - If the segment was affected by the RNMP and the reference median speed exceeded 30 km/h, the new assumed speed was set at 29 km/h to align with VBZ traffic models and account for tram speed regulation systems.
- **Bus Segments:**
  - For all bus segments affected by the RNMP, if the reference median speed exceeded 30 km/h, the new assumed speed was set at 27 km/h, as defined in VBZ traffic models.

  - Unlike trams, buses do not benefit from independent tracks, making them fully subject to the RNMP speed reductions.

The slightly higher speed for trams reflects their ability to maintain more consistent speeds across the network. This is partly due to the presence of speed regulators on trams, which function similarly to cruise control systems in cars. These regulators help ensure that trams adhere to the designated speed limits, contributing to a smoother and more reliable operation (VBZ, 2024) [4].

#### Comparison of Reference and RNMP Speed Regimes

By integrating statistical measures from the reference period with the newly implemented speed limits under the RNMP, it was possible to quantify the expected changes in operational speeds. This analysis allows for a detailed assessment of how the RNMP impacts different segments of the public transport network, both at a granular level and across the entire system.

The difference in speed between the reference period and the new speed regime was calculated using the following Formula 4.3:

$$\Delta\text{Speed} = \text{Speed}_{\text{reference}} - \text{Speed}_{\text{RNMP}} \tag{4.3}$$

Where: - $\Delta$Speed is the change in speed between the reference period and the new speed regime. - $\text{Speed}_{\text{reference}}$ is the median speed from the reference period. - $\text{Speed}_{\text{new}}$ is the new speed limit from the RNMP.

#### Comparison of Travel Time Needs Before and After RNMP

To evaluate the temporal impacts of the RNMP, the analysis focused on calculating travel times based on the median speeds for each segment. Following a methodology similar to VBZ's Wirkungskontrolle (VBZ, 2019), the effective travel time for each segment was determined by considering its respective length. This provided a clear representation of the Median Time Need required during the reference period. The Formula 4.4 used for calculating the travel time for each segment is as follows:

$$\text{Travel Time} = \frac{\text{Segment Length}}{\text{Speed}} \tag{4.4}$$

Where: - Travel Time is the time required to travel through a segment, expressed in seconds. - Segment Length is the length of the segment in meters. - Speed is the average speed for the segment, expressed in meters per second (m/s).

For each segment, the travel time under the new speed regime resulting from the RNMP was calculated and compared to the median travel time of the reference period. The difference between these values represented the Additional Time Need for those segments due to the implementation of the RNMP. This systematic approach allowed for a precise and detailed

[4] Personal communication with VBZ experts, January 2025.

assessment of the temporal impacts on both tram and bus operations. The Formula 4.5 used for calculating the additional time need is:

$$\Delta\text{Additional Time Need} = \text{Travel Time}_{\text{RNMP}} - \text{Travel Time}_{\text{reference}} \quad (4.5)$$

Where: - ΔTravel Time is the additional time required due to the speed regime changes. - Travel $\text{Time}_{\text{new}}$ is the travel time under the new speed regime. - Travel $\text{Time}_{\text{reference}}$ is the travel time during the reference period.

### Data Presentation Criteria

To effectively present the impact of the RNMP, both visualizations and tabular summaries were generated, ensuring a structured approach to analysing public transport performance. The presentation of results was categorized according to the following key dimensions:

- **Transport mode:** Separate analyses were conducted for trams and buses.
- **Traffic peak periods:** Data were categorized into HVZ1 and HVZ2.
- **Travel direction:** Results were differentiated for Direction 1 and Direction 2.

### Levels of Data Representation

The results were visualized and summarized at three distinct levels:

- **Network-wide overview:** A system-wide representation highlighting aggregate changes in travel times and speed variations across the entire public transport network.
- **Detailed 20-meter segment analysis:** High-resolution visualizations providing localized insights into specific routes, ensuring a fine-grained understanding of RNMP effects.
- **Each tram and bus line separately:** Tabular representations detailing travel time variations between lines, with a focus on the most affected lines.

### Classification and Data Interpretation

To ensure meaningful representation, classification into five classes was initially performed using the Natural Breaks method, optimizing class boundaries to minimize intraclass variance and maximize interclass differences (Zhang et al., 2021).

Following consultations with VBZ experts in December 2024[5], an additional class was manually introduced. This extra class, represented in gray, highlighted segments with minimal deviations (e.g., 0-0.0001 km/h) to ensure clarity on areas unaffected by the RNMP.

For segments experiencing speed reductions, a red-toned gradient was applied, illustrating differences between the reference period and the new speed regime. This method emphasized areas with significant impacts, improving interpretability.

[5]Discussion with VBZ experts during project consultations, December 2024.

#### Grid-Based Visualization Approach

To facilitate high-resolution analysis, each combination of transport mode, HVZ period, and travel direction was mapped separately. This resulted in a total of eight visualizations per level of analysis: Bus HVZ1 Direction 1, Bus HVZ1 Direction 2, Bus HVZ2 Direction 1, Bus HVZ2 Direction 2, Tram HVZ1 Direction 1, Tram HVZ1 Direction 2, Tram HVZ2 Direction 1, Tram HVZ2 Direction 2

To further improve spatial resolution, the study area was divided into six grids (A–F), allowing for zoomed-in, detailed visualizations of each section.

#### Contextual Elements in Data Representation

To enhance interpretability, the following elements were incorporated:

- Stop names were shortened to reduce visual clutter. In Zurich, stop names are typically labeled as *Zurich, Stopname*; for clarity in visualizations, the prefix *Zurich,* was removed while retaining the stop name itself.

- Hydrological layers, including rivers and lakes, were integrated to accurately depict Zurich's geographic context.

- City boundaries, building footprints, green areas and transit stop locations were included to provide spatial reference points.

### 4.2.7 Hotspot Analysis

#### Getis-Ord Gi* Statistics

To analyse spatial relationships of the additional travel times resulting from the RNMP within the transport network, a neighbourhood structure was developed to encapsulate the local context of each segment. A distance-based methodology defined spatial neighbours as all adjacent segments within a 420-meter radius, encompassing ten 20-meter segments both before and after the focal segment. This window size effectively represented local spatial dynamics while minimizing the influence of distant, unrelated areas [6].

The `spdep` (Bivand, 2022) package in R was utilized to construct a spatial weights matrix, quantifying the influence of neighbouring segments. Row-normalization ensured comparability across all segments, facilitating a balanced evaluation of localized spatial effects.

The Getis-Ord Gi* (Getis and Ord, 1992) statistic was employed to identify clusters of significant travel time variations. This method evaluates whether observed spatial events exhibit clustering by comparing the local sum of a variable (e.g., travel time differences), within a specified neighbourhood to the global average. The standardized Gi* statistic, expressed as a Z-score, indicates the statistical significance of clustering. A near-zero Gi* value implies a random distribution of spatial events. In contrast, highly positive or negative Gi* values suggest clusters of high or low values, respectively. Positive Gi* values correspond to hotspots, while negative values correspond to cold spots (Songchitruksa and Zeng, 2010; Getis and Ord, 1992). The Gi*

[6] Defined together with VBZ experts, during project consultations, December 2024.

score is calculated as follows:

$$Z(G_i^*) = \frac{\sum_{j=1}^{n} w_{ij}x_j - \bar{x}\sum_{j=1}^{n} w_{ij}^2}{s\sqrt{\frac{n\sum_{j=1}^{n} w_{ij}^2 - \left(\sum_{j=1}^{n} w_{ij}\right)^2}{n-1}}}$$

where:

- $ZG_i$: Standardized Gi statistic for segment $i$,
- $x_j$: Value of the variable of interest at segment $j$,
- $w_{ij}$: Spatial weight between segment $i$ and $j$,
- $\bar{x}$: Global mean of the variable of interest,
- $S$: Standard deviation of the variable of interest,
- $n$: Total number of segments.

If the calculated Gi* values exceed a significance threshold (e.g., $ZG_i^* > 1.96$ for the 95% confidence level), the corresponding segment is identified as part of a statistically significant cluster. This indicates a hotspot for high values or a coldspot for low values. The results were visualized through static and interactive maps using the `tmap` (Tennekes, 2018) package in R, offering intuitive representations of significant clusters:

The Z-score results were visualized on maps using contrasting color palettes, ensuring clear differentiation between localized hotspots and cold spots. This approach enhanced the interpretability of spatial clustering patterns, effectively highlighting areas with significantly higher or lower additional travel times.

## 4.3 Accessibility Analysis

### 4.3.1 Elevation Data on Passenger Network

To assess the accessibility of the tram stops *Löwenbräu* and *Quellenstrasse*, elevation data was integrated into the analysis to account for its influence on walking speeds and, consequently, on public transport accessibility and comfort. Variations in elevation can significantly affect pedestrian movement, making it a critical factor in evaluating the impact of stop adjustments on accessibility (Aghabayk et al., 2021).

To incorporate elevation data into the pedestrian network analysis, the network geometry was refined by segmenting all paths into 20-meter sections. This segmentation was performed using the `st_segmentize` function from the `sf` package in R (Pebesma, 2018), ensuring a higher spatial resolution for analysing elevation variations. For each segment, the midpoint was calculated and used as a reference location for elevation extraction. These midpoints were then transformed into the WGS84 coordinate reference system (EPSG:4326) to ensure alignment with the spatial reference of the elevation raster data.

Elevation values were obtained from a digital elevation model (DEM) using the `raster` package in R (Hijmans, 2024). The extracted elevation values, corresponding to the midpoints of each segment, were subsequently assigned to their respective network segments. This process resulted in a geospatial dataset enriched with elevation information, as illustrated in Figure 4.2. The elevation-enhanced dataset was then used to refine walking speed calculations, incorporating the effects of elevation changes on pedestrian movement and public transport accessibility..

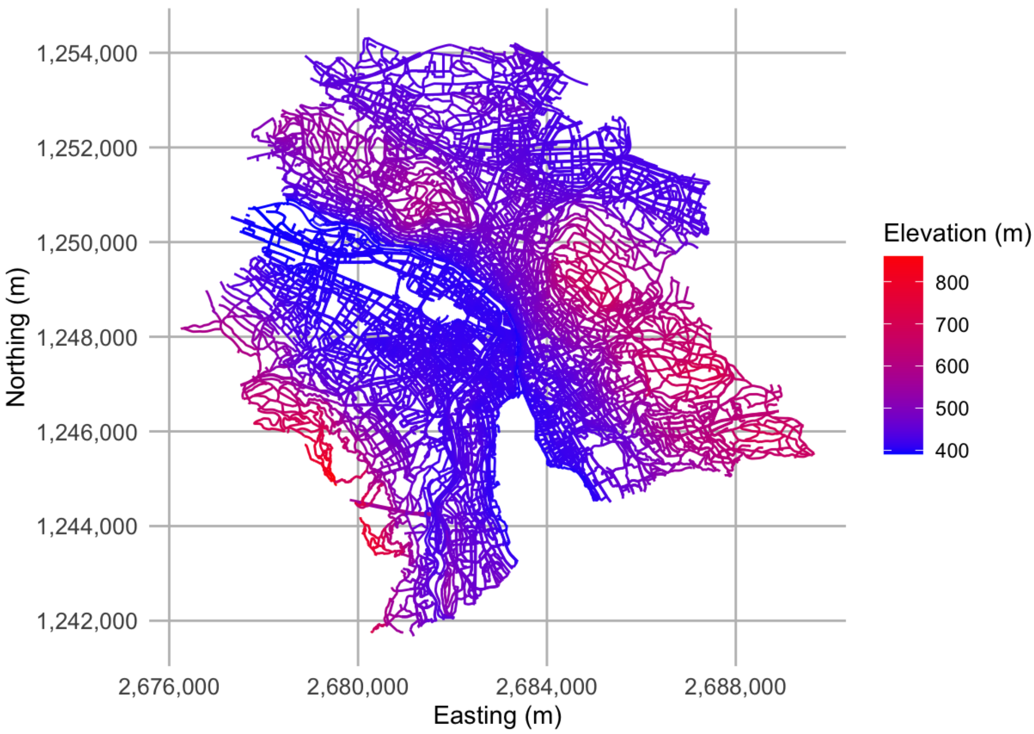



**Figure 4.2:** Pedestrian network combined with digital elevation model for the City of Zurich

### 4.3.2 Calculation of Walking Speeds

Walking speeds were calculated for each segment of the pedestrian network by incorporating slope effects, following the methodology adapted from (Aghabayk et al., 2021). A base walking speed of 4.86 km/h was used, reflecting the average walking speed on flat terrain observed in controlled experiments. This base speed was then adjusted for slope effects, with specific adjustments applied to account for gentle and steep inclines or declines (Aghabayk et al., 2021).

For each 20-meter segment, the slope was calculated as the ratio of the elevation difference ($\Delta h$) to the segment length ($\Delta x$). The walking speed was then modified according to the following Formula 4.6:

$$\text{Adjusted Walking Speed} = \text{Base Speed} \times 1\ \ \text{Slope Factor} \tag{4.6}$$

Where: - Base Speed = 4.86 km/h is the base walking speed on flat terrain. - Slope Factor is determined based on the slope of the terrain, defined as the ratio of the elevation change ($\Delta h$) to the segment length ($\Delta x$). - For steep uphill (+12% slope): Slope Factor = $-0.25$ (reduction by 25%). - For gentle uphill (+6% slope): Slope Factor = $-0.10$ (reduction by 10%). - For gentle downhill (-6% slope): Slope Factor = 0.05 (increase by 5%). - For steep downhill (-12% slope): Slope Factor = 0.10 (increase by 10%). - For flat terrain (0–1% slope): Slope Factor = 0 (no change).

This formula provides the adjusted walking speed for each segment based on the slope, ensuring a more accurate representation of walking conditions across the pedestrian network.

These adjustments were applied to ensure that the walking speeds accurately reflect the influence of terrain on the movement of the pedestrian. In addition, a minimum walking speed of 0.5 km/h was enforced to prevent unrealistically low values for extreme cases. The adjusted walking speeds were subsequently used to calculate the walking times for each segment in the network. The walking time ($T$) was calculated using the Formula similar as in Formula 4.4.

### 4.3.3 Evaluation of Accessibility and Walking Travel Times

The analysis focused on the transit stops *Löwenbräu* and *Quellenstrasse*, selected due to the potential consideration of consolidating these stops as part of public transport network adjustments. Stop consolidation is being explored as a possible measure to mitigate the additional travel time resulting from the introduction of *Tempo 30*, aiming to enhance operational efficiency while maintaining accessibility. Given Zurich's high density of transit stops, such adjustments would not compromise overall network accessibility but may lead to longer walking distances for some users, as explained in subsection 2.2.2.

To assess the impact of stop relocation on accessibility, four scenarios were analysed, evaluating how the stops serve surrounding households (building entrances) and how changes affect the population within different walking zones:

1. **Baseline Scenario:** The accessibility zones of both stops were analysed together to determine their combined coverage and assess how the current configuration serves the surrounding area. If a building was located within the walking zones of both stops but in different categories, the shorter walking time was assigned.

2. **Löwenbräu Only:** This scenario examined the impact of removing the *Quellenstrasse* stop, leaving only *Löwenbräu* in operation. The analysis quantified accessibility losses and shifts in the number of buildings and people within each walking zone.

3. **Quellenstrasse Only:** Conversely, this scenario assessed the effects of removing the *Löwenbräu* stop, keeping only *Quellenstrasse* operational. Changes in accessibility were analysed similarly to the previous scenario.

4. **Hypothetical Stop:** A hypothetical scenario evaluated the effect of replacing both stops with a single station positioned between them.[7]

[7]The exact location of the new stop was determined in consultation with VBZ to ensure alignment with

Walking times were calculated for each scenario based on walking distances and elevation data. The accessibility zones were classified into four categories:

$$\begin{aligned} &\text{Zone 1:} \quad \leq 2 \text{ minutes} \\ &\text{Zone 2:} \quad 2-5 \text{ minutes} \\ &\text{Zone 3:} \quad 5-10 \text{ minutes} \\ &\text{Zone 4:} \quad > 10 \text{ minutes} \end{aligned} \tag{4.7}$$

8

The four scenarios were visualized in accessibility maps, where walking times were displayed in distinct categories using different colors. These maps provided a detailed view of the surrounding network, highlighting accessibility within the immediate vicinity of the stops under each scenario. Additionally, bar plots were created for each scenario to illustrate the number of buildings within each walking zone, allowing for a comparative analysis of accessibility changes across different configurations.

operational and infrastructure considerations.

[8]This categorization was determined in consultation with VBZ experts in January 2025.

# Chapter 5

# Results

The results outlined in this Chapter build upon the methodological framework introduced in Chapter 4. The first part of this Chapter investigates the effects of the RNMP on tram and bus services (Section 5.1). It begins with a detailed statistical assessment of travel time changes across the entire network (Section 5.1.1). To further illustrate these findings, Section 5.1.2 provides visual representations of the bus network for Direction 1, while Section 5.1.4 presents close-up analyses of key affected areas. The results for Direction 2 buses and trams Direction 1 and 2 are included in Appendices A, B, and C. Additionally, Section 5.1.5 applies a hotspot analysis using the Getis-Ord Gi* method to identify locations most affected. To analyse the effects for each line separately, Section 5.1.6 presents the results of a detailed line-by-line analysis.

The second part of the Chapter 4.3 shifts focus to the accessibility analysis between the public transport stops *Löwenbräu* and *Quellenstrasse* for four different scenarios. The results are presented in two key sections. First, Section 5.2.1 visualizes walking accessibility zones, illustrating how far pedestrians can travel within defined time intervals under different stop configurations. These maps provide insights into how accessibility changes when modifying or consolidating transit stops. Second, Section 5.2.2 quantifies these effects by analysing the number of building entrances accessible within each walking zone, enabling a data-driven comparison of accessibility impacts across different scenarios.

## 5.1 Effects of the RNMP

### 5.1.1 Statistical Analysis over the entire network

Table 5.1 presents the results of the RNMP's impact on bus travel times over the entire network in direction 1 and 2. The table outlines the median additional time and Q3 (75th percentile) additional time for buses compared to the reference period. The median additional time for buses during HVZ1 and HVZ2 in each direction ranges from 15:19 minutes to 16:50 minutes, with Q3 additional time ranging from 23:00 minutes to 26:01 minutes across the respective directions. Summing up the results for both directions, Table 5.2 shows that the total median additional time for HVZ1 is 31:31 minutes, while for HVZ2 it increases slightly to 32:09 minutes. The Q3 values show a similar trend, with a total of 47:42 minutes for HVZ1 and 49:01 minutes for HVZ2.

#### Overview entire bus network

| HVZ | Dir | Median Additional Time (mm:ss) | Q3 Additional Time (mm:ss) |
|---|---|---|---|
| HVZ1 | 1 | 15:19 | 24:16 |
| HVZ1 | 2 | 16:12 | 23:26 |
| HVZ2 | 1 | 16:50 | 26:01 |
| HVZ2 | 2 | 15:19 | 23:00 |

**Table 5.1:** Impact of the RNMP on bus travel times: Median and Q3 additional time (mm:ss) compared to the reference period from April–May 2023.

| HVZ | Median Additional Time (mm:ss) | Q3 Additional Time (mm:ss) | Mean Additional Time per 100m (s) |
|---|---|---|---|
| HVZ1 | 31:31 | 47:42 | 0.57 |
| HVZ2 | 32:09 | 49:01 | 0.56 |

**Table 5.2:** Summed additional travel times for buses in both directions during HVZ1 and HVZ2: Median, Q3, and mean additional time per 100 meters (s).

Similarly, Table 5.3 provides data for tram travel times. The median additional time for trams ranges from 2:10 minutes to 2:47 minutes during HVZ1 and HVZ2, while the Q3 additional time varies from 3:51 minutes to 5:23 minutes. When combining the results for both directions, Table 5.4 reveals that the total median additional time for HVZ1 is 4:29 minutes, increasing to 5:01 minutes for HVZ2. The total Q3 values for trams follow a similar pattern, with 9:06 minutes in HVZ1 and 9:14 minutes in HVZ2. These results indicate that, while trams are generally less affected by the RNMP than buses, the impact is still noticeable across both HVZ periods.

**Overview entire tram network**

| HVZ | Dir | Median Additional Time (mm:ss) | Q3 Additional Time (mm:ss) |
|---|---|---|---|
| HVZ1 | 1 | 2:19 | 4:00 |
| HVZ1 | 2 | 2:10 | 5:06 |
| HVZ2 | 1 | 2:14 | 3:51 |
| HVZ2 | 2 | 2:47 | 5:23 |

**Table 5.3:** Impact of the RNMP on tram travel times: Median and Q3 additional time (mm:ss) compared to the reference period from April–May 2023.

| Traffic Period | Median Additional Time (mm:ss) | Q3 Additional Time (mm:ss) | Mean Additional Time per 100m (s) |
|---|---|---|---|
| HVZ1 | 4:29 | 9:06 | 0.019 |
| HVZ2 | 5:01 | 9:14 | 0.022 |

**Table 5.4:** Summed additional travel times for trams in both directions during HVZ1 and HVZ2: Median, Q3, and mean additional time per 100 meters (s).

The results presented in Tables 5.1, 5.2, 5.3, and 5.4 will be further visualized in the following Section 5.1.2.

### 5.1.2 Visualisations of statistical analysis

This subsection presents visualizations of the statistical analysis conducted on the entire bus network in Direction 1, the additional travel time (in seconds) during HVZ1 and HVZ2 is illustrated in Figures 5.1 and 5.2, respectively. Detailed views of the bus lines across grids A through F are shown in Figures 5.4 to 5.15. Their corresponding legends can be found in Figures 5.16 (HVZ1) and 5.17 (HVZ2).

For the bus network in Direction 2, the visualizations are provided in Appendix A.The tram network visualizations for Direction 1 are included in Appendix B, while the visualizations for Direction 2 are available in Appendix C.

### 5.1.3 Comparison of Additional Median Time Need in the Bus Network during HVZ1 and HVZ2 (Direction 1)

Figures 5.1 and 5.2 show the additional median travel time for buses during HVZ1 and HVZ2 (Direction 1), respectively, in 20-meter segments. Both figures use a color gradient to represent varying additional travel times, with HVZ1 showing times ranging from 0.00 to 1.18 seconds and HVZ2 from 0.00 to 0.19 seconds. The areas with the largest delays compared to the reference period, are marked by darker colors, highlighting regions with significant travel time increases. In general, HVZ1 shows a slightly broader range of additional time compared to HVZ2, indicating more significant delays in some areas during HVZ1.

**Overview of Additional Median Time Need in the Bus Network during HVZ1 (Direction 1)**

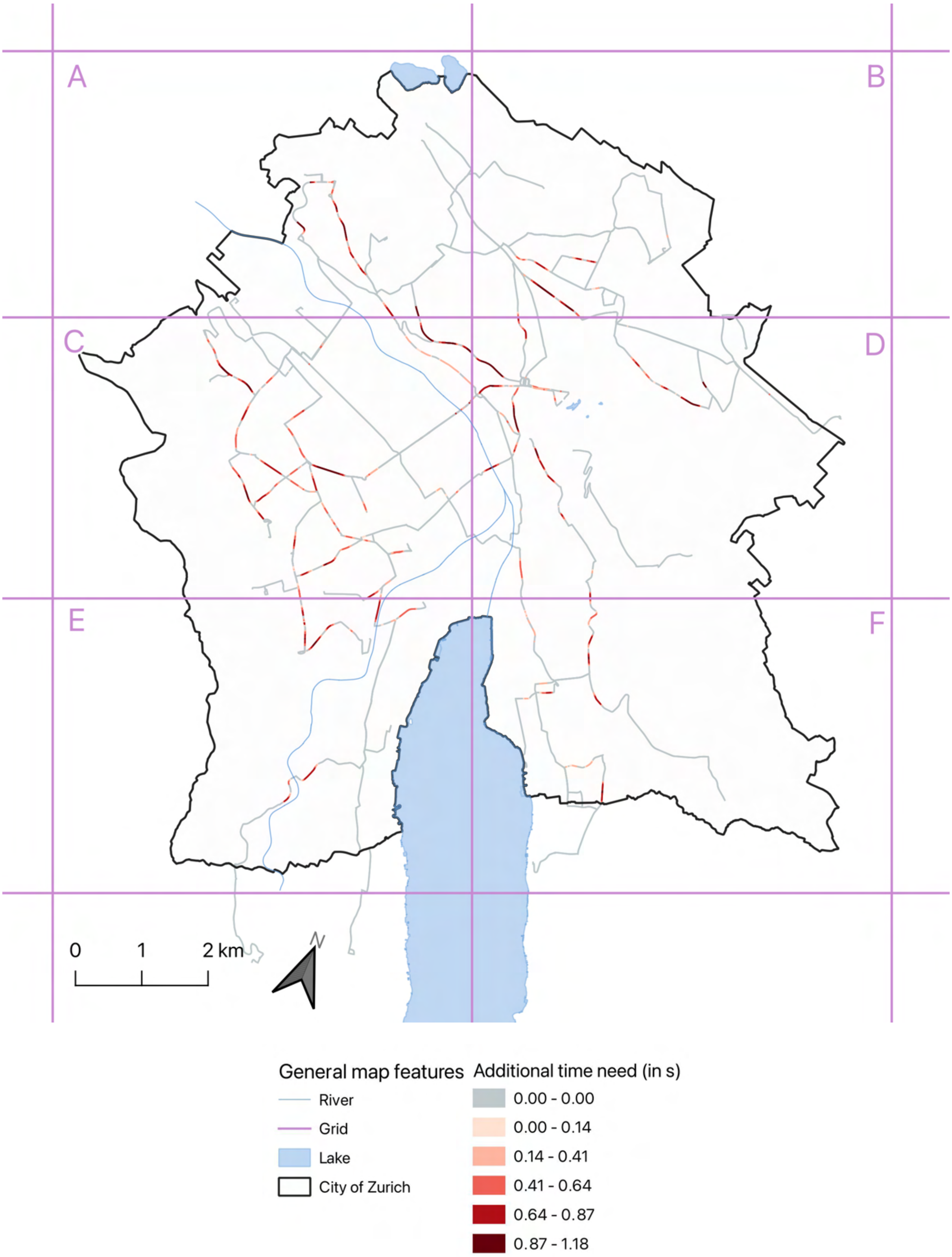



**Figure 5.1:** Overview of the bus network during HVZ1 (Direction 1), displayed in 20-meter segments. The median additional time need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

**Overview of Additional Median Time Need in the Bus Network during HVZ2 (Direction 1)**

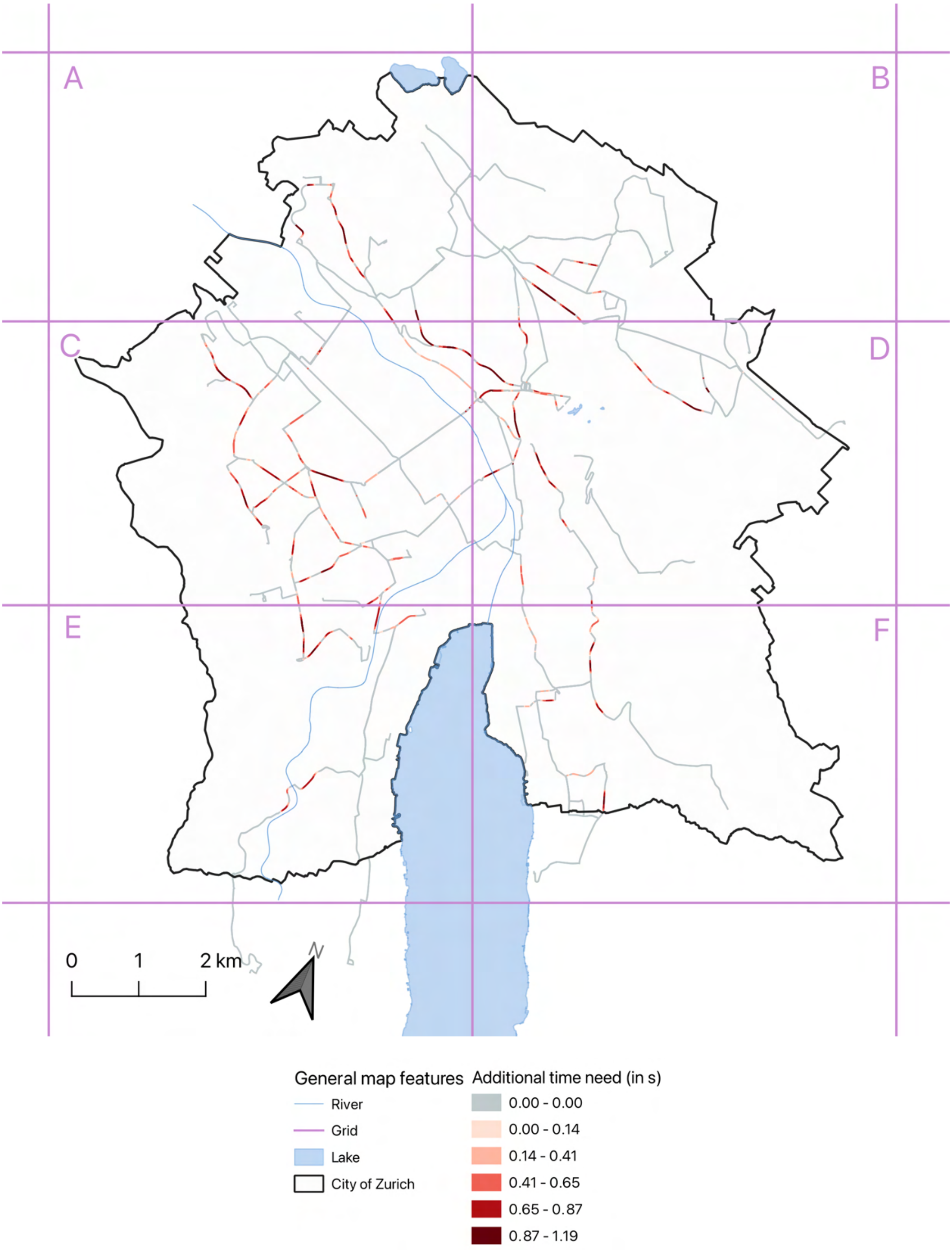



**Figure 5.2:** Overview of the bus network during HVZ2 (Direction 1), displayed in 20-meter segments. The median additional time need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

### 5.1.4 Close-up Views of the Bus Network (Direction 1)

The following Section 5.1.4 provide a close-up analysis of these key areas between stops, highlighting where the most substantial increases in travel time occur and how they vary between HVZ1 and HVZ2.

#### Comparison of Additional Time Needed (in s) for Buses in Grid A during HVZ1 and HVZ2, Direction 1

In both HVZ1 and HVZ2, several 20-meter segments show significant increases in additional travel time, particularly along the route between Schwert and Frankental (Figure 5.3). This section experiences a notable rise in travel time due to the implemented speed changes, as shown in Figures 5.4 and 5.5. The highest additional time is observed between Segantinistrasse and Giblenstrasse, reaching nearly 1.2 seconds per 20-meter segment. These values consistently exceed those of surrounding sections, highlighting the substantial impact of speed regulation changes along this part of the route.

In the comparison between HVZ1 and HVZ2, as shown in Figures 5.4 and 5.5, the overall patterns of additional travel time are quite similar, with minimal changes observed in the eastern part of the grid. However, specific segments, such as those between Heizenholz and Geringstrasse, show slightly lower delays during HVZ2. This indicates that the speed changes introduced by the RNMP had a greater impact during HVZ1.

Overall, the comparison between HVZ1 and HVZ2 shows that while many sections exhibit similar patterns, the additional time decreases in front of bus stops due to the deceleration while approaching the stop. Once the bus accelerates again, additional time increases, especially in areas with more pronounced speed changes. In general, hotspots of additional time are concentrated in the middle sections, while the edges tend to have lower values, reflecting the acceleration phase after the stops.


**Figure 5.3:** Detailed view of additional time need between stops Schwert and Frankental for bus in HVZ1 Direction 1

#### Comparison of Additional Time Needed (in s) for Buses in Grid B during HVZ1 and HVZ2, Direction 1

When examining the additional travel time for buses in Grid B during HVZ1 (Figure 5.6) and HVZ2 (Figure 5.7), it is evident that the western part of the grid is most affected by the speed changes introduced by the RNMP. In both HVZ1 and HVZ2, the segments with the highest deviations from the reference period are located between Rautihalde and Rautistrasse, Felsenbergstrasse and Sackzelg, Albisrieden and Triemli, Hubertus and Altes Krematorium, and Friesenberg and Höfliweg. Additionally, in the northeastern part of the grid, the section between Im Wingert and Waidspital also shows higher values. These locations exhibit significant increases in travel time due to the speed restrictions, with values rising to around 1.18 seconds in HVZ1 and 1.19 seconds in HVZ2. When comparing the two periods, HVZ1 and HVZ2, the overall patterns of additional travel time are very similar, with only slight differences.

Compared to Grid A, which has more concentrated segments with higher additional time values, Grid B shows a more dispersed distribution of segments with increased travel times, especially in the western regions. These findings suggest that while both HVZ1 and HVZ2 are affected by the new speed regulations, the differences between the two periods are relatively minor, and the additional time increases are mainly seen in the same sections across both HVZs.

#### Comparison of Additional Time Needed (in s) for Buses in Grid C during HVZ1 and HVZ2, Direction 1

In Grid C, during both HVZ1 and HVZ2, the highest differences in additional time compared to the reference period are observed, particularly in the northern part of the grid. The segments between Im Hagacker and Laubegg, Manesseplatz and Waffenplatzstrasse, as well as Verenastrasse and Bahnhof Leimbach, are most notably affected, as shown in Figures 5.8 and 5.9.

When comparing HVZ1 and HVZ2, only slight changes are visible. For example, between Im Hagacker and Hegianwandweg, there are slightly higher values in HVZ1. The affected segments remain the same, with the primary difference being the degree to which they are impacted by the speed adjustments. While the locations of these segments remain consistent across both time periods, the extent of the additional time varies slightly between HVZ1 and HVZ2.

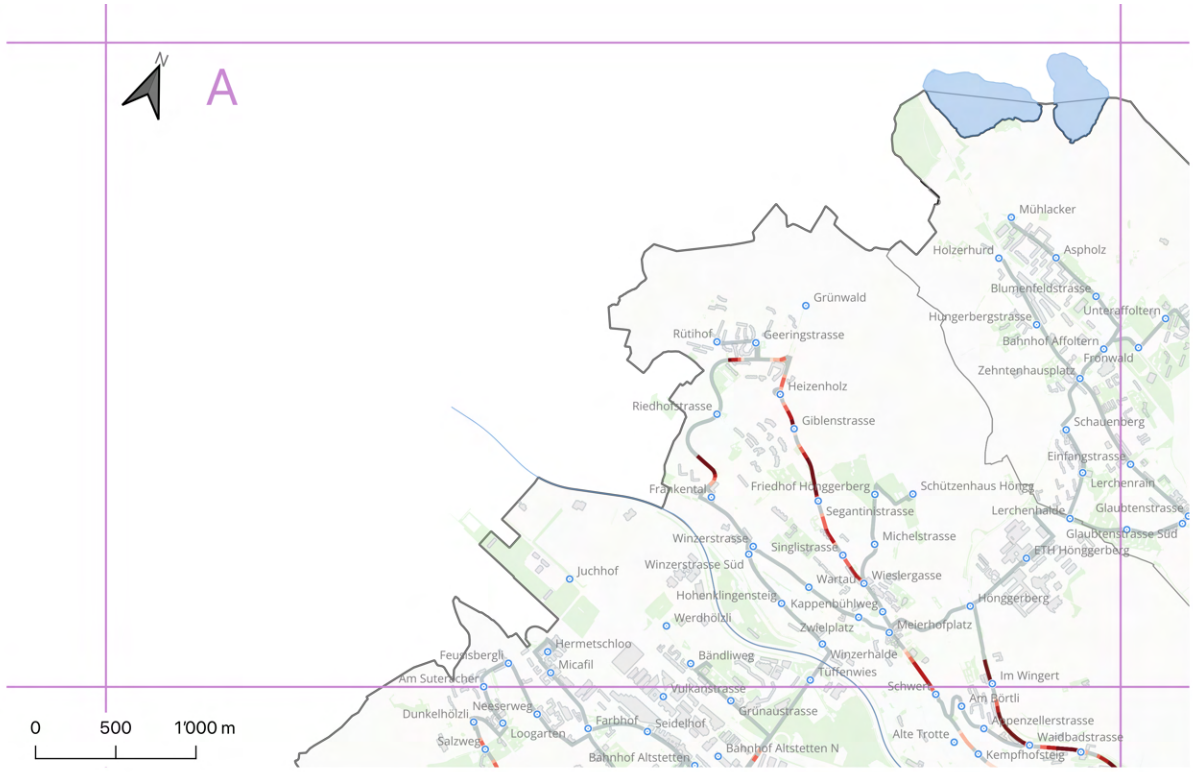



**Figure 5.4:** Additional time need (in s) for buses in Grid A during HVZ1, Direction 1, in 20-meter segments. See Figure 5.16 for detailed legend.

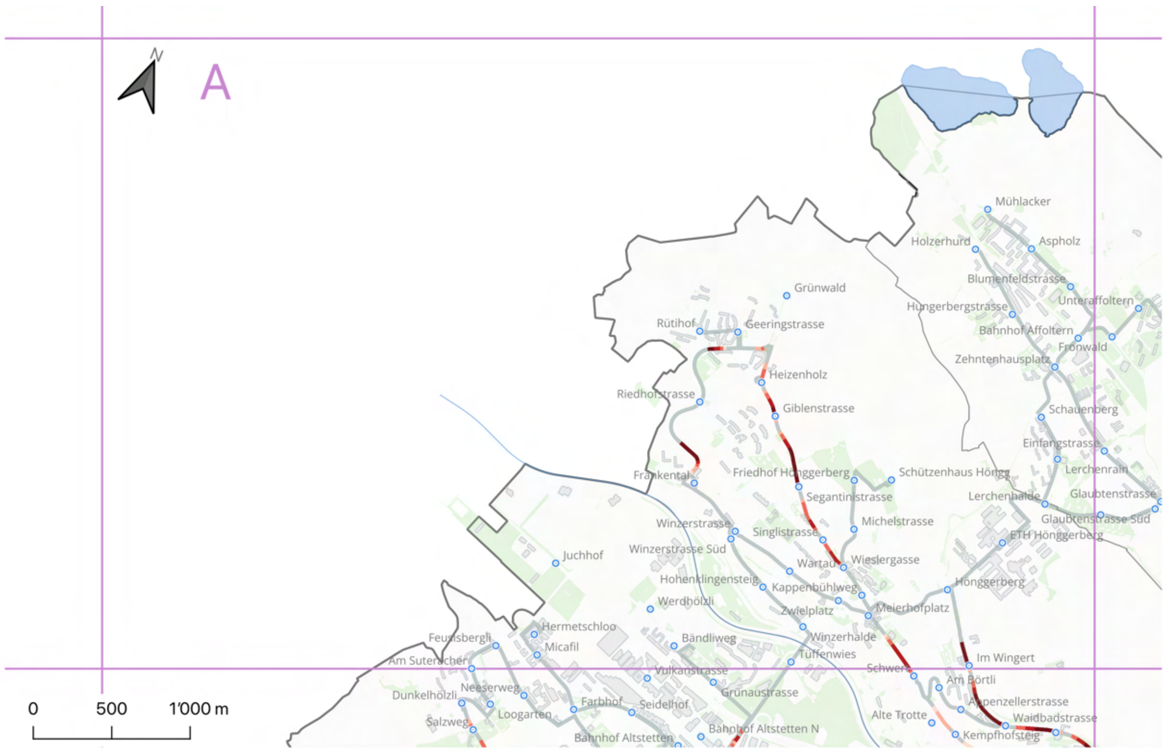



**Figure 5.5:** Additional time need (in s) for buses in Grid A during HVZ2, Direction 1, in 20-meter segments. See Figure 5.17 for detailed legend.


**Figure 5.6:** Additional time need (in s) for buses in Grid B during HVZ1, Direction 1, in 20-meter segments. See Figure 5.16 for detailed legend.


**Figure 5.7:** Additional time need (in s) for buses in Grid B during HVZ2, Direction 1, in 20-meter segments. See Figure 5.17 for detailed legend.

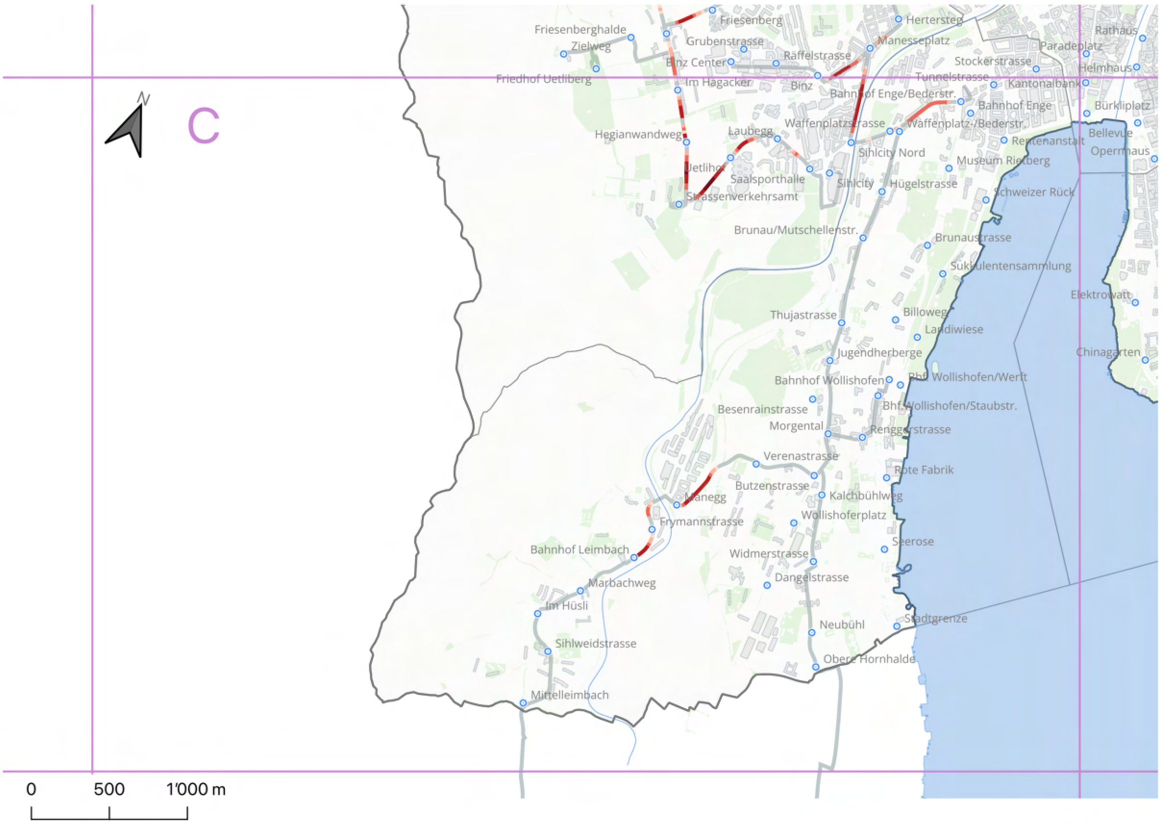



**Figure 5.8:** Additional time need (in s) for buses in Grid C during HVZ1, Direction 1, in 20-meter segments. See Figure 5.16 for detailed legend.

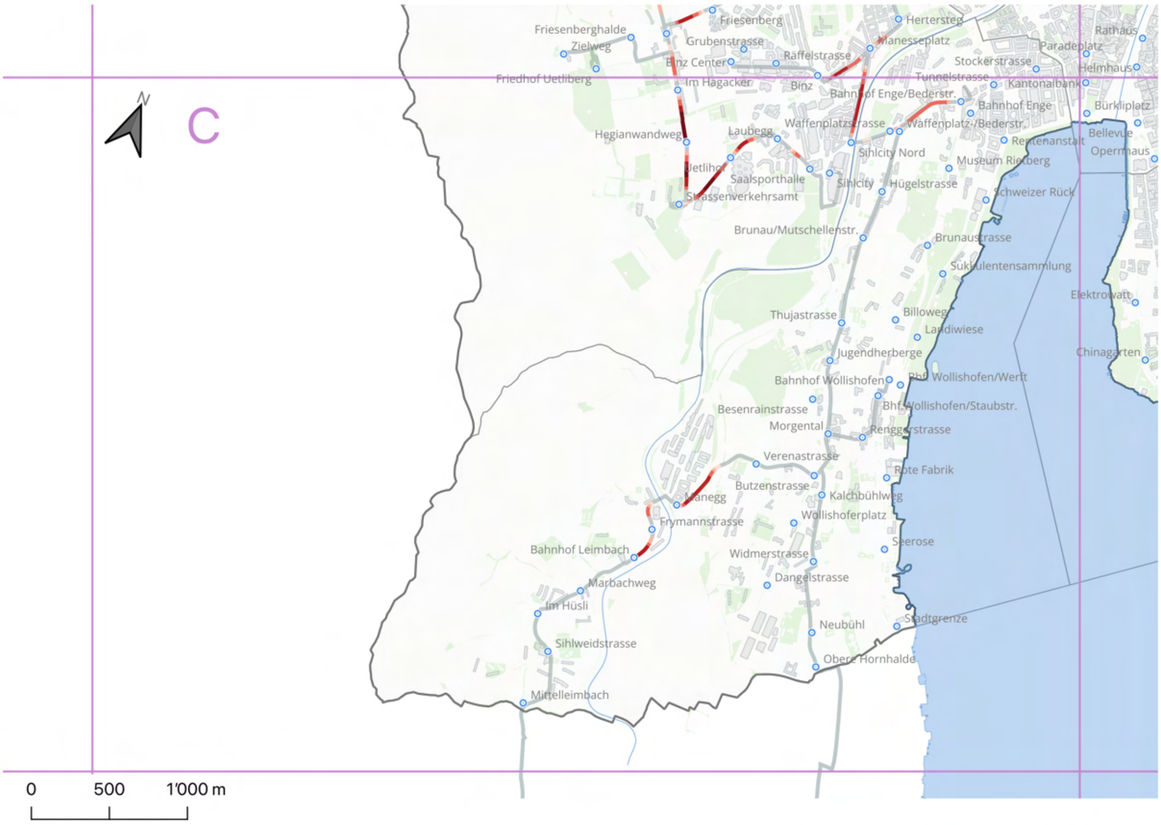



**Figure 5.9:** Additional time need (in s) for buses in Grid C during HVZ2, Direction 1, in 20-meter segments. See Figure 5.17 for detailed legend.

#### Comparison of Additional Time Needed (in s) for Buses in Grid D during HVZ1 and HVZ2, Direction 1

In Grid D, the western and southwestern sections experience the most significant changes in additional time (0.87–1.19 s), particularly between Neuaffoltern and Bahnhof Oerlikon Nord, as shown in Figures 5.10 and 5.11. Additional time increases are also evident between Mötteliweg and Chaletweg, as well as between Maillartstrasse and Neunbrunnen. These changes in travel times align with the expected impact of speed regulation adjustments.

When comparing HVZ1 and HVZ2, only slight differences are observed, with the locations of the affected segments remaining consistent. The degree of additional time required, however, varies slightly between the two periods, with HVZ1 generally showing marginally higher values than HVZ2.

#### Comparison of Additional Time Needed (in s) for Buses in Grid E during HVZ1 and HVZ2, Direction 1

In Grid E, during both HVZ1 and HVZ2, the highest values of additional time are observed in several long segments, particularly between Waidspital and Weihersteig, Lägernstrasse and Rotbuchstrasse, and Schaffhauserstrasse and Scheuchzerstrasse. Additionally, the segment between Frohburg and Friedrichstrasse is also notably affected by additional time, as shown in Figures 5.12 and 5.13.

#### Comparison of Additional Time Needed (in s) for Buses in Grid F during HVZ1 and HVZ2, Direction 1

In Grid F, the most significant difference between the reference period and the new speed regime is observed between Kirche Fluntern and Hofstrasse, as well as in several 20-meter segments between Hofstrasse and Kapfstrasse, as shown in Figures 5.14 and 5.15. Additionally, shorter segments between Botanischer Garten and Hegibachplatz, and around Klinik Hirslanden, are also affected by the additional time need caused by the speed regulation changes. Similarly to other grids, the comparison between HVZ1 and HVZ2 shows minor variations in affected areas, with HVZ1 generally showing slightly higher values for the additional time required.

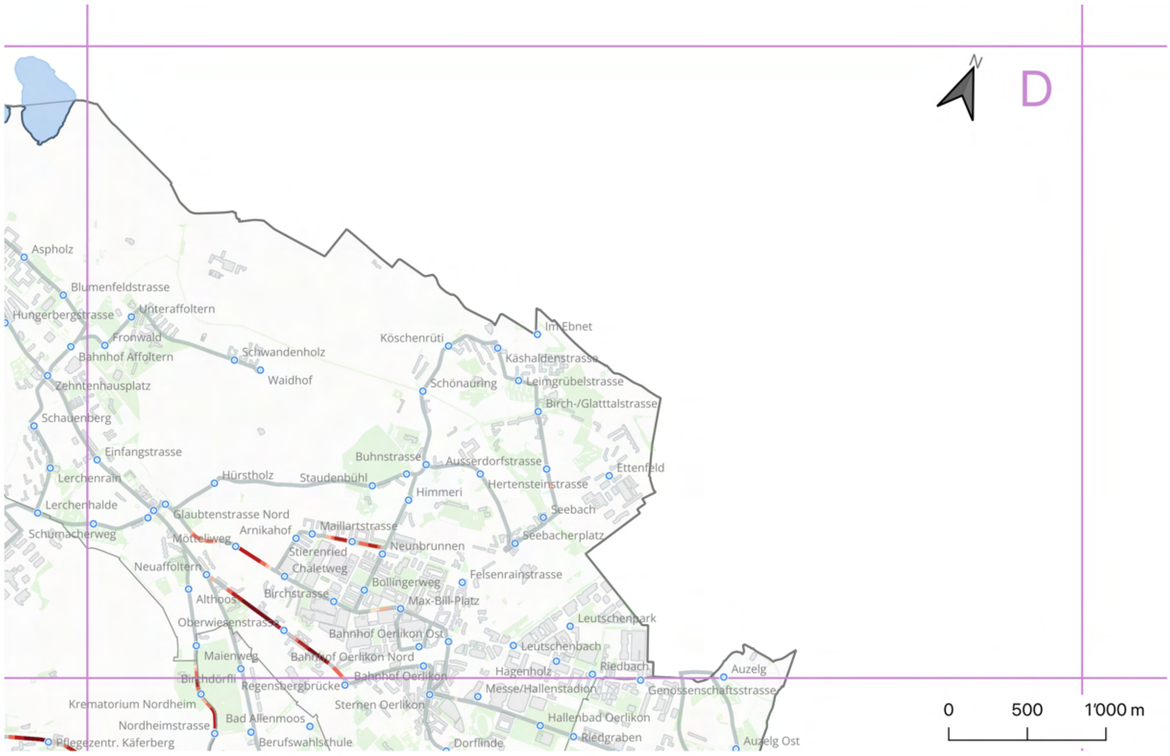



**Figure 5.10:** Additional time need (in s) for buses in Grid D during HVZ1, Direction 1, in 20-meter segments. See Figure 5.16 for detailed legend.

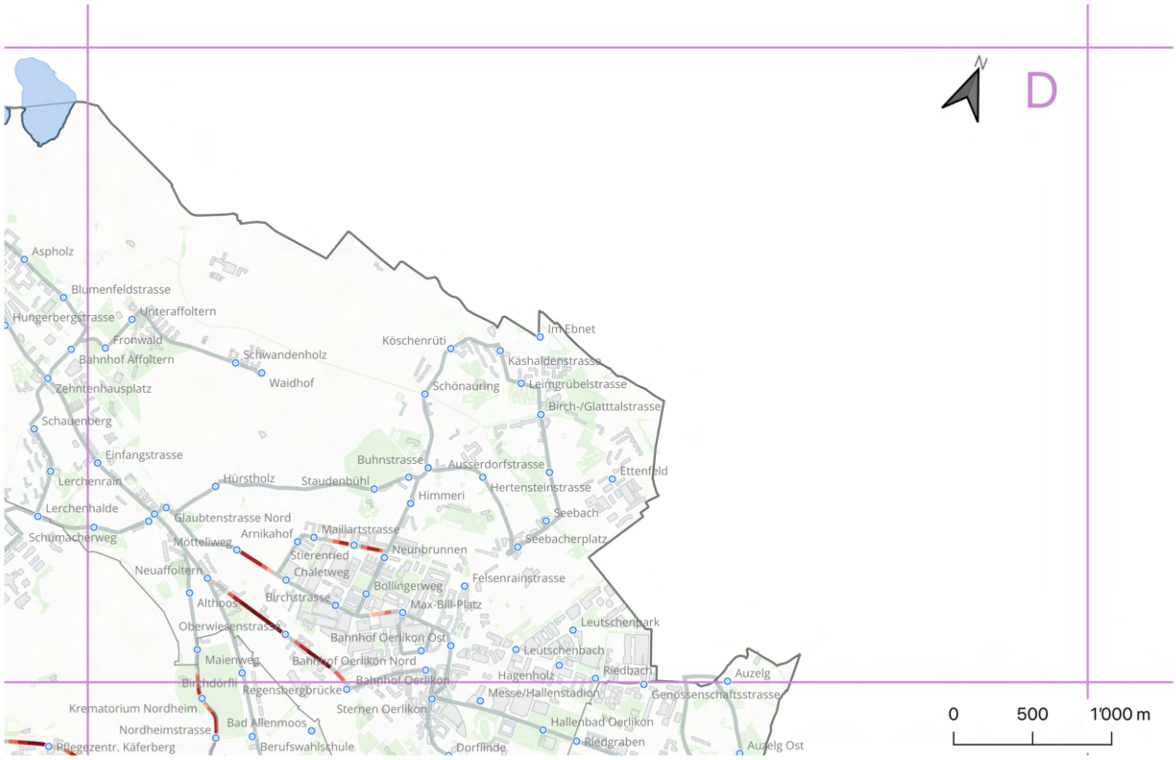



**Figure 5.11:** Additional time need (in s) for buses in Grid D during HVZ2, Direction 1, in 20-meter segments. See Figure 5.17 for detailed legend.

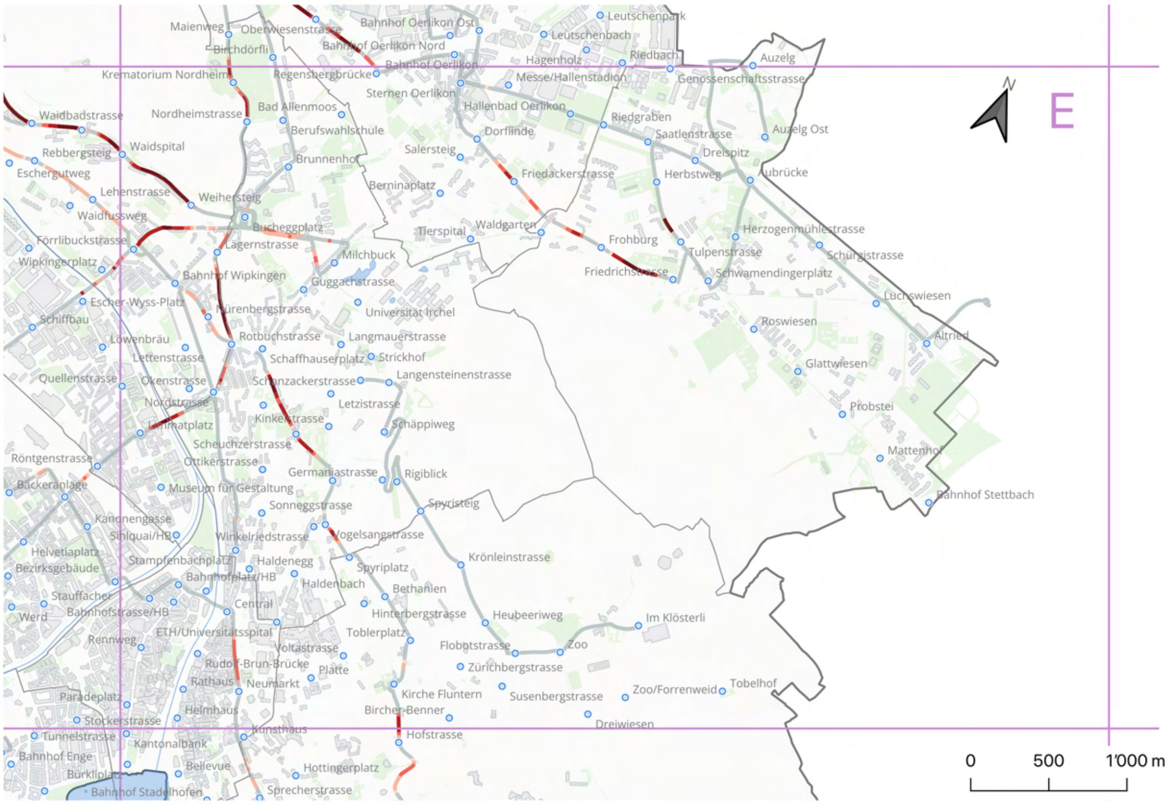



**Figure 5.12:** Additional time need (in s) for buses in Grid E during HVZ1, Direction 1, in 20-meter segments. See Figure 5.16 for detailed legend.

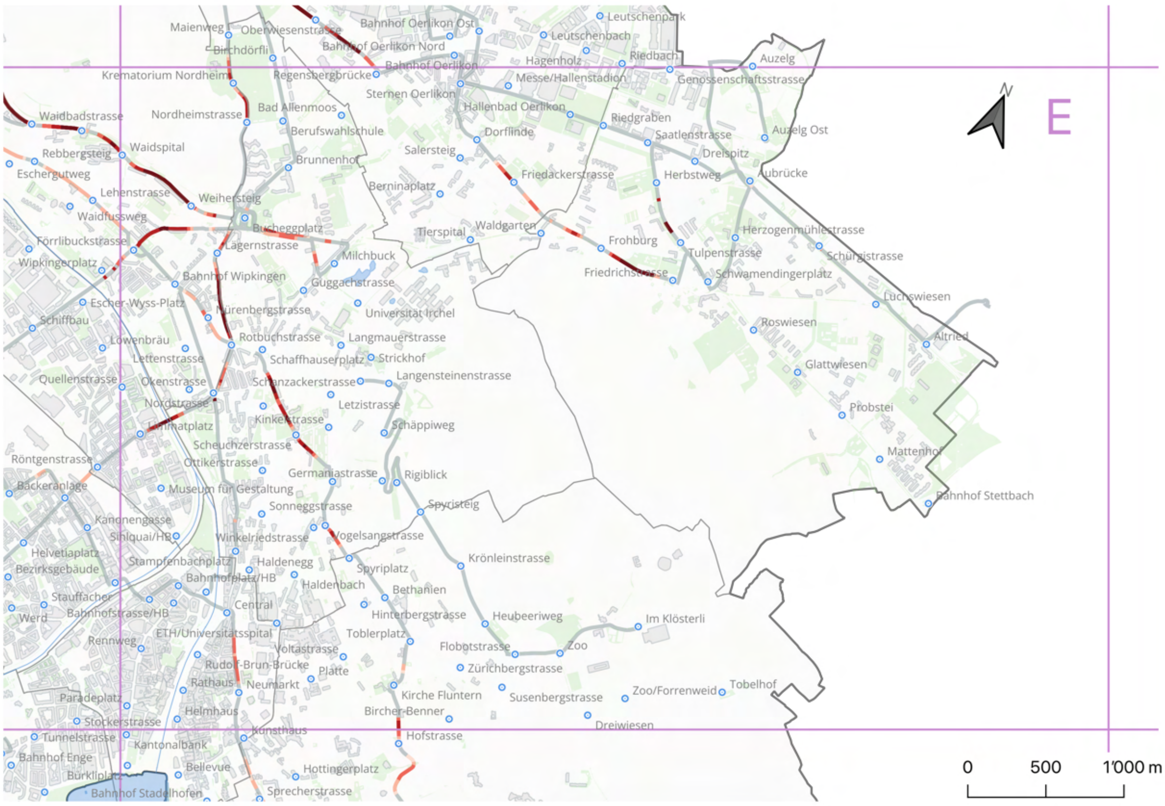



**Figure 5.13:** Additional time need (in s) for buses in Grid E during HVZ2, Direction 1, in 20-meter segments. See Figure 5.17 for detailed legend.


**Figure 5.14:** Additional time need (in s) for buses in Grid F during HVZ1, Direction 1, in 20-meter segments. See Figure 5.16 for detailed legend.

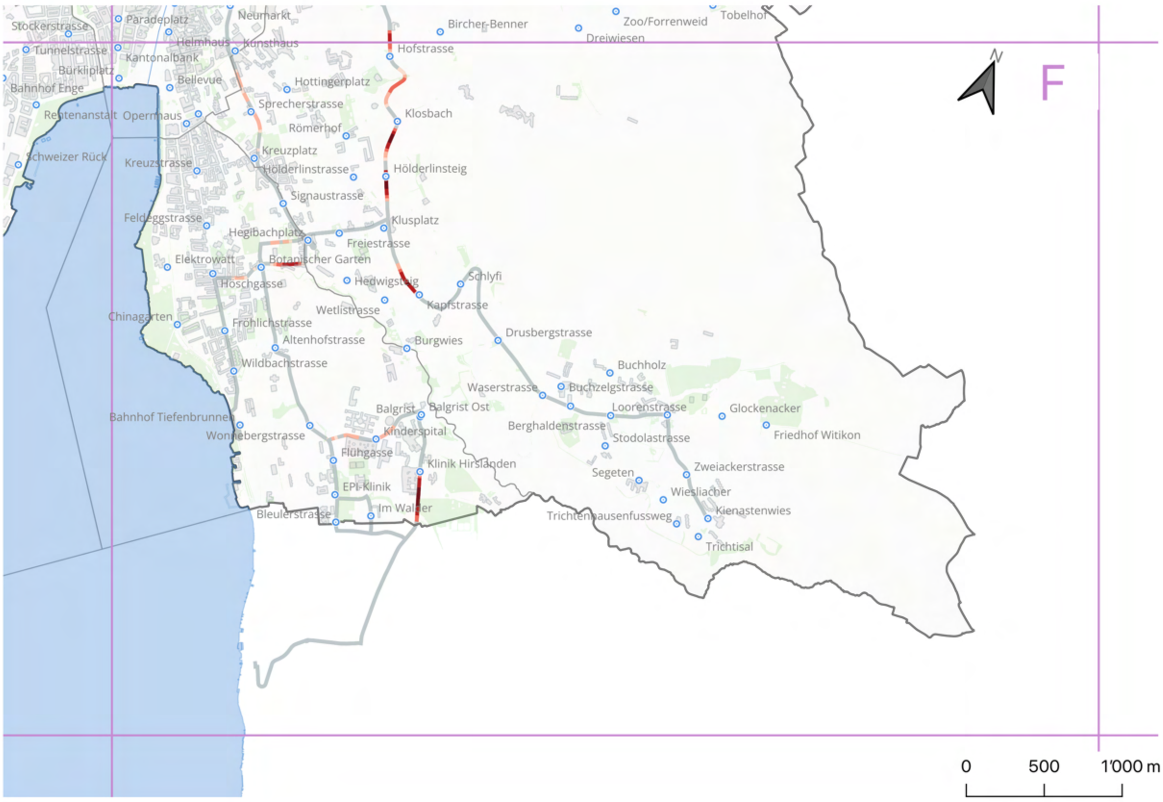



**Figure 5.15:** Additional time need (in s) for buses in Grid F during HVZ2, Direction 1, in 20-meter segments. See Figure 5.17 for detailed legend.

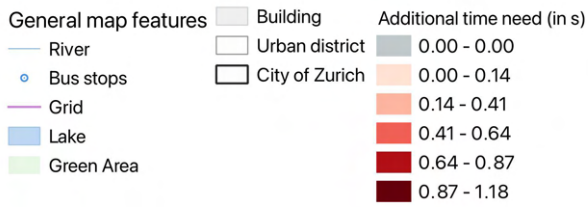



**Figure 5.16:** Legend for buses in HVZ1 Direction 1 for grid A-F

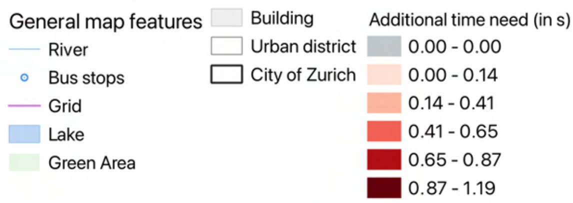



**Figure 5.17:** Legend for buses in HVZ2 Direction 1 for grid A-F

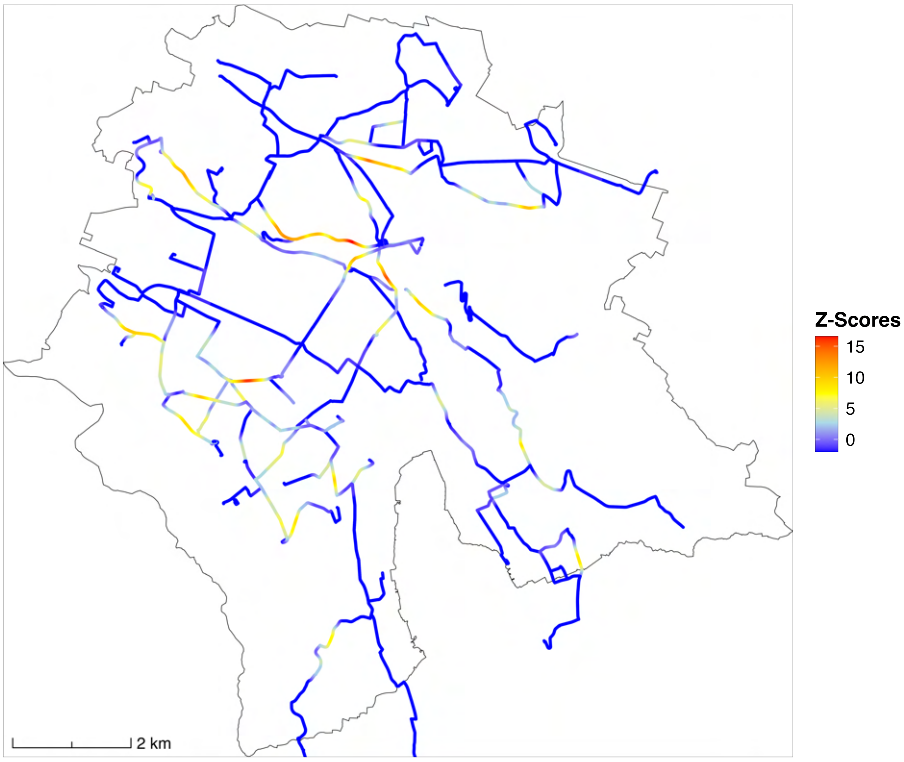
### 5.1.5 Hotspot Analysis

#### Bus network

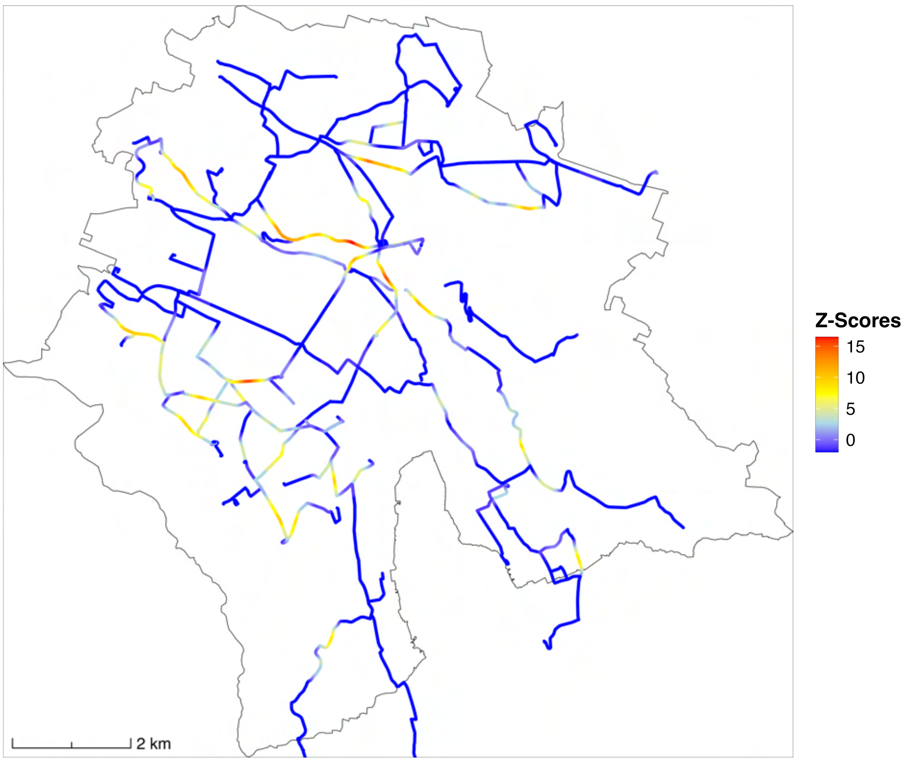
The analysis of the spatial distribution of Gi* Z-Scores for bus segments during HVZ1 and HVZ2 are presented in this section. For direction 1, as shown in Figure 5.18b, the central and western regions of the bus network consistently emerge as hotspots of additional time need during both HVZ1 and HVZ2. In particular, segments near key intersections exhibit significant additional time need across both periods. While the overall patterns remain similar, HVZ2 displays slightly higher Gi* Z-Scores in the southeastern part of the network, suggesting moderately broader impacts during this traffic period.

For direction 2, Figure 5.19 the spatial distribution of Gi Z-Scores* for HVZ1 and HVZ2 highlights differences in the clustering of additional travel times. HVZ2 exhibits more intense and spatially extended hotspots, particularly in key segments where Z-scores exceed 10–15, indicating a greater concentration of travel time delays. In contrast, HVZ1 shows slightly fewer and less intense clusters, suggesting relatively lower congestion levels during the morning peak. The distribution of cold spots remains consistent across both maps, though some segments that were neutral in HVZ1 exhibit stronger clustering effects in HVZ2. Overall, the results indicate that evening congestion leads to more pronounced and widespread travel time delays, whereas the morning peak period presents a more localized pattern of additional travel times.

### Z-Scores Bus Direction 1



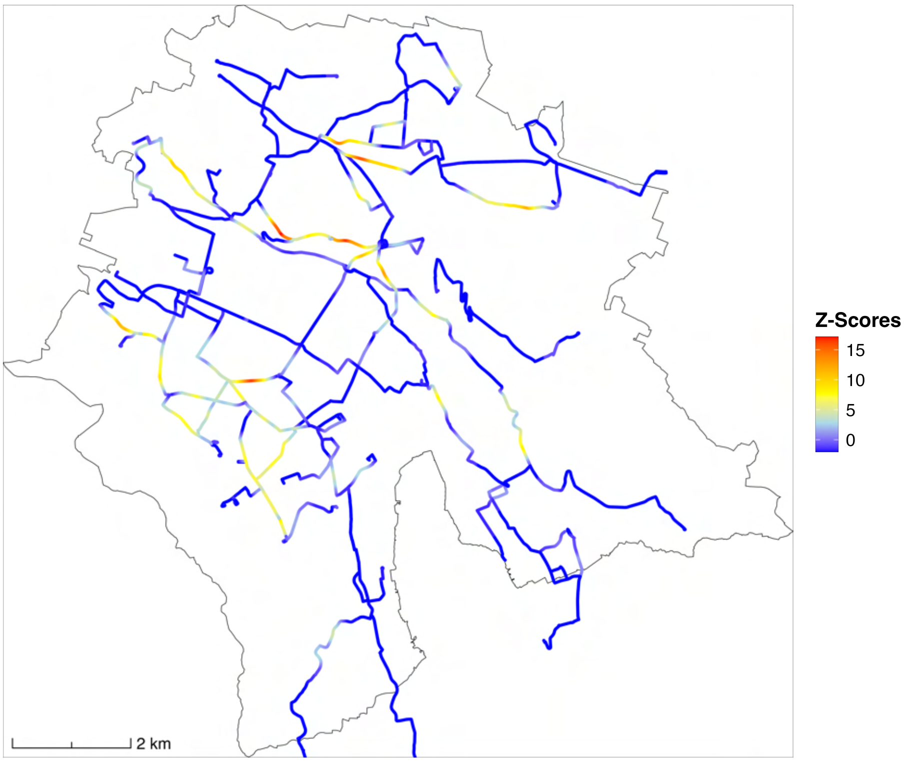

**(a)** HVZ1 Bus Dir1



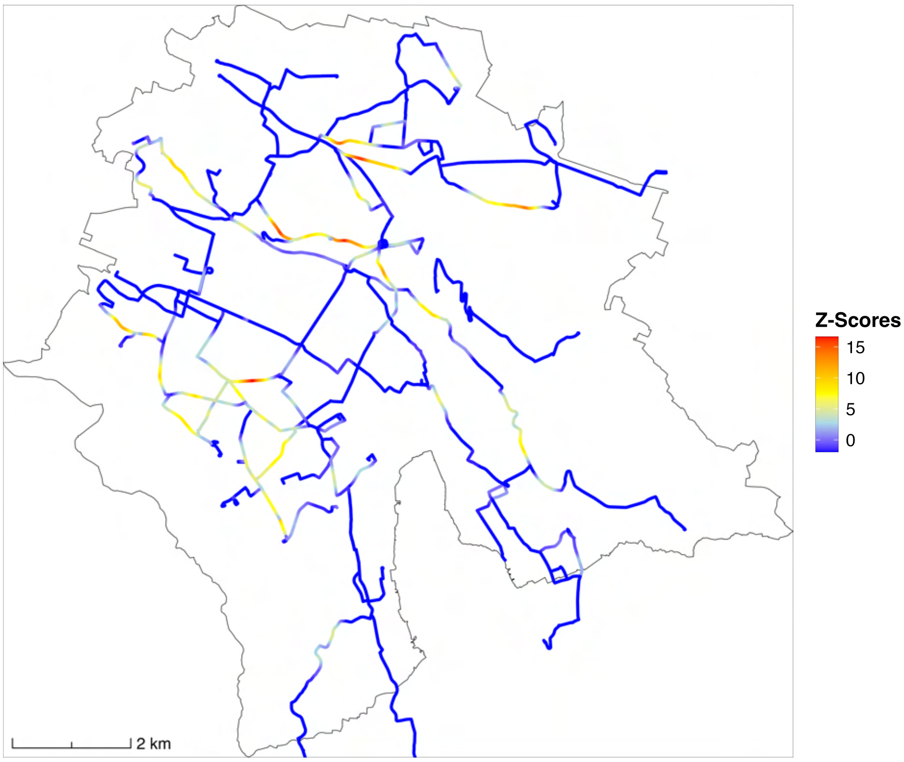

**(b)** HVZ2 Bus Dir1

**Figure 5.18:** Spatial distribution of Gi* Z-Scores for Direction 1 bus segments.

#### Z-Scores Bus Direction 2




(a) HVZ1 Bus Dir2




(b) HVZ2 Bus Dir2

**Figure 5.19:** Spatial distribution of Gi* Z-Scores for Direction 2 bus segments.

#### Tram network

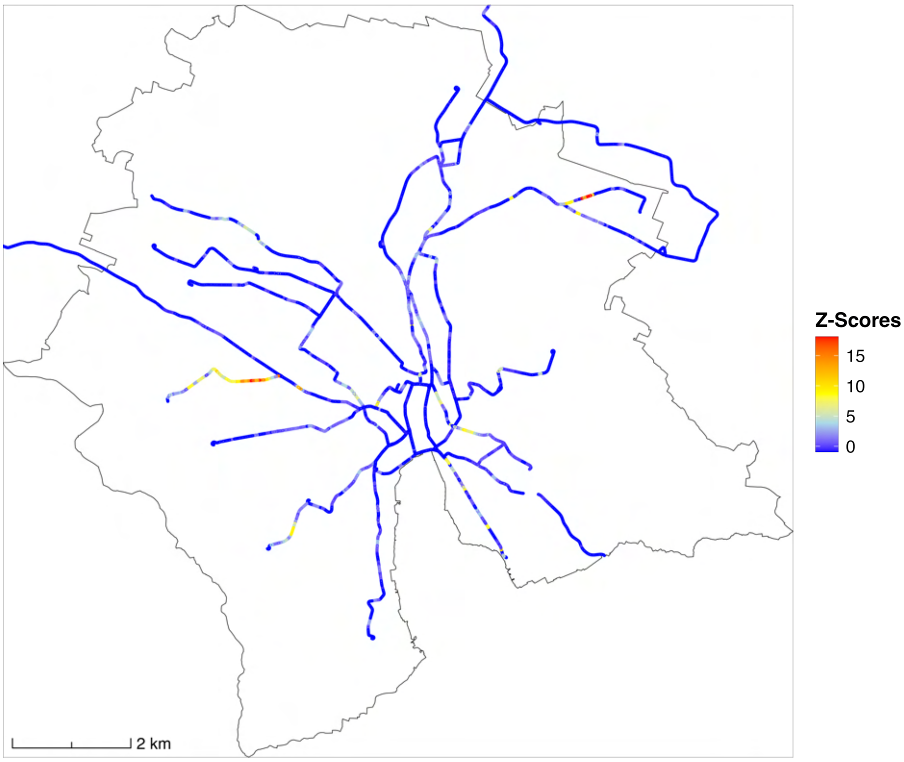
The analysis of the spatial distribution of Gi* Z-Scores for tram segments in HVZ1 and HVZ2 reveals consistent patterns of additional time need across both traffic periods, with notable differences in specific areas.

The spatial distribution of Gi Z-Scores* for tram segments in direction 1 during HVZ1 and HVZ2 appears very similar, with consistent hotspot locations across both maps. The clusters of high Z-scores (above 10–15) are found in the same areas for both peak periods, indicating that the patterns of travel time delays remain stable throughout the day. This similarity suggests that the congestion effects on tram travel times are comparable during both the morning and evening peak periods, with no significant variations in the spatial distribution of delays.

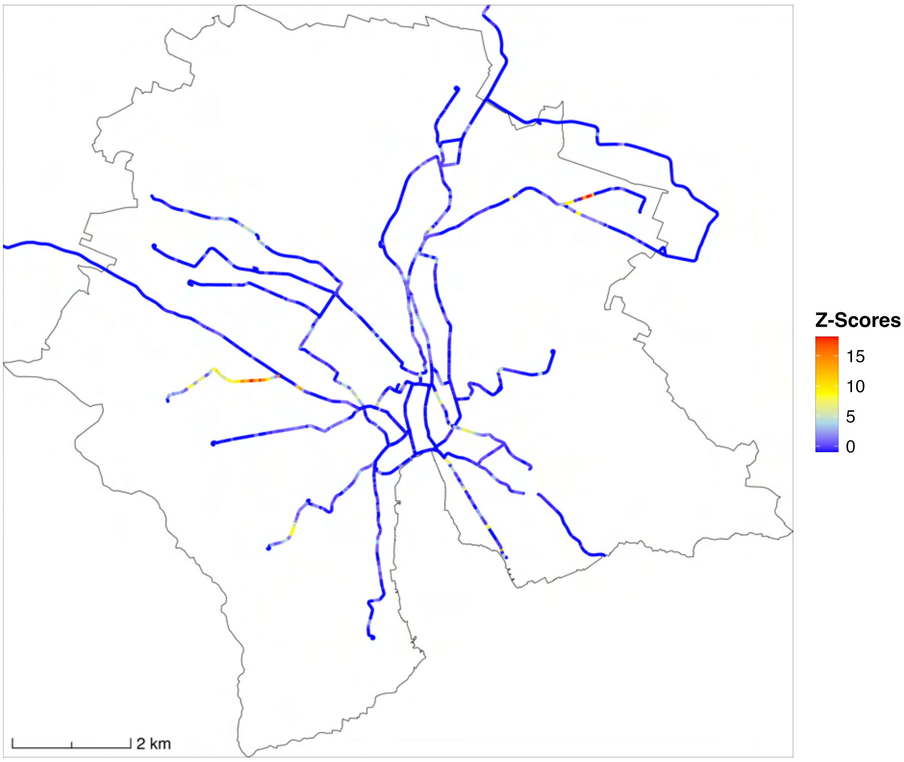
The spatial distribution of Gi Z-Scores* for tram segments in direction 2 during HVZ1 and HVZ2 appears highly similar, with hotspot locations remaining largely unchanged between the two peak periods. The clusters of high Z-scores (above 8–12) occur in the same areas, indicating that the pattern of travel time delays is stable throughout the day. Notably, the maximum Z-scores in this direction reach only 12, whereas in tram direction 1, Z-scores reached up to 15

Compared to the bus hotspots, the tram hotspots are less pronounced and occur less frequently, suggesting that trams experience fewer and more localized delays. This highlights the greater variability and intensity of additional travel times in the bus network, whereas tram delays remain relatively stable and confined to specific segments.

**Z-Scores Tram Direction 1**



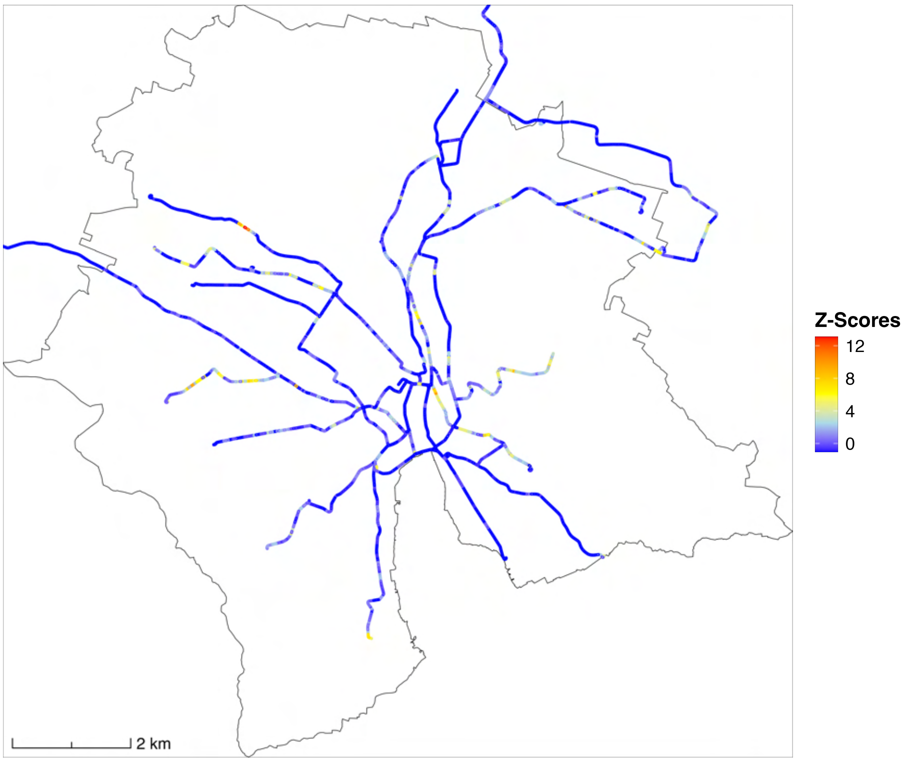

(a) HVZ1 Tram Dir1



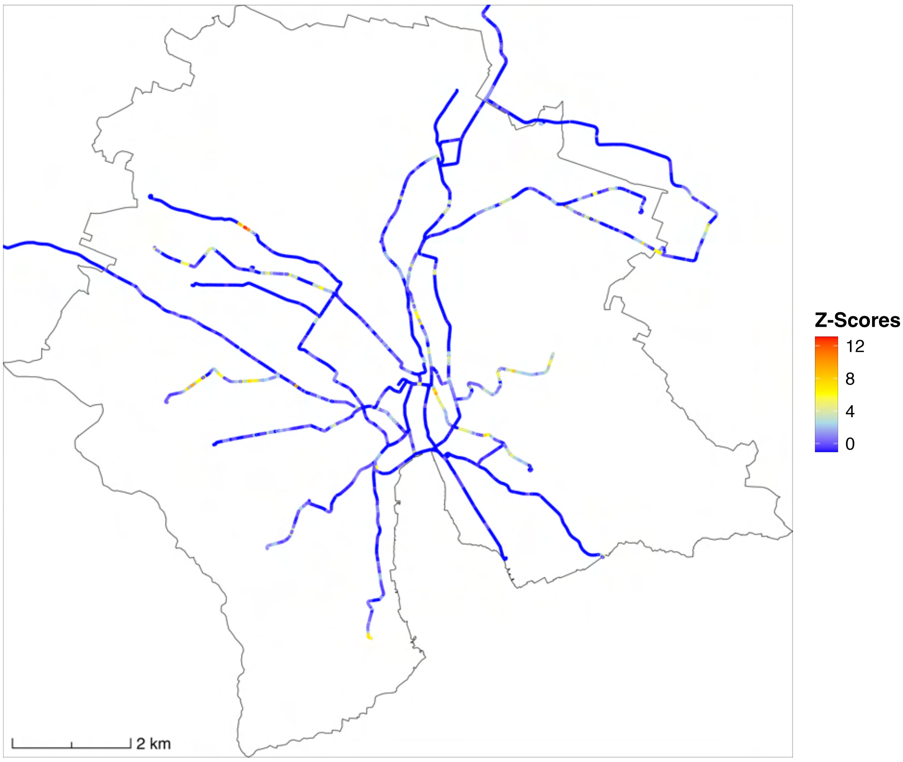

(b) HVZ2 Tram Dir1

**Figure 5.20:** Spatial distribution of Gi* Z-Scores for direction 1 tram segments.

### Z-Scores Tram Direction 2




**(a)** HVZ1 Tram Dir2




**(b)** HVZ2 Tram Dir2

**Figure 5.21:** Spatial distribution of Gi* Z-Scores for Direction 2 tram segments.

### 5.1.6 Statistical Analysis over separate lines

This section provides a detailed analysis of each individual bus and tram line during HVZ1 and HVZ2. In this analysis, the additional travel times from Direction 1 and Direction 2 are summed, as the total duration of a complete trip—including the turnaround time—provides a more comprehensive measure of how significantly a line is affected by the speed reductions. This approach allows for a better assessment of the cumulative impact on operational efficiency and scheduling adjustments required due to the regulatory changes. The additional times presented in this section are modeled estimates derived from computational calculations, reflecting the expected impact of RNMP on individual lines bus and tram lines.

#### Overview of the Most Affected Bus Lines

Figures 5.22 and 5.23 show the bus lines with the highest additional time compared to the median reference period during HVZ1 and HVZ2, respectively.

In HVZ1, bus line 33 experiences the highest additional time with 299.1 seconds, followed by line 67 with 288.7 seconds, and line 89 with 276.9 seconds, as shown in Figure 5.22. The additional time range of the five most affected lines for HVZ1 spans from 299.1 to 210.4 seconds.

However, in HVZ2, the order of affected bus lines changes, with bus line 33 still experiencing the highest additional time at 291.9 seconds, followed by line 89 with 287.8 seconds, and line 67 with 282.3 seconds, as illustrated in Figure 5.23. The range of the five highest additional times for HVZ2 is between 291.9 and 215.3 seconds.

This shift between HVZ1 and HVZ2 highlights the varying impact of speed regulation changes on these bus lines during the two peak hours. Specifically, line 33, line 89, and line 67 remain consistent in the top three most affected lines, although their rankings shift slightly between the two periods.

The highest difference between HVZ1 and HVZ2 is observed in line 83, where HVZ1 shows 28.6 seconds more of additional time compared to HVZ2 throughout the line.

**Bus lines with the highest additional time in seconds during HVZ1**

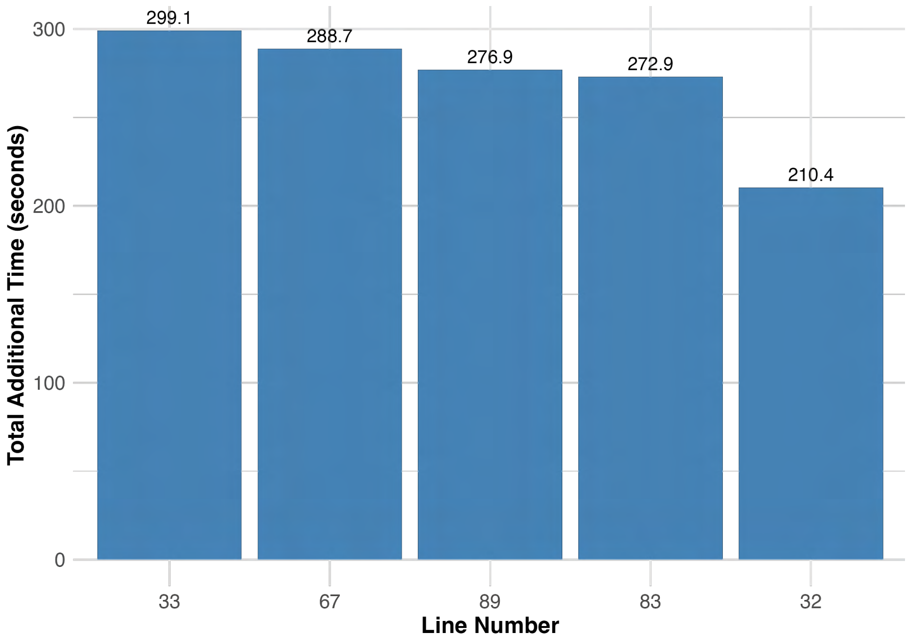



**Figure 5.22:** Bus lines with the highest additional time compared to the median reference period during HVZ1

**Bus Lines with the Highest Additional Time in Seconds during HVZ2**

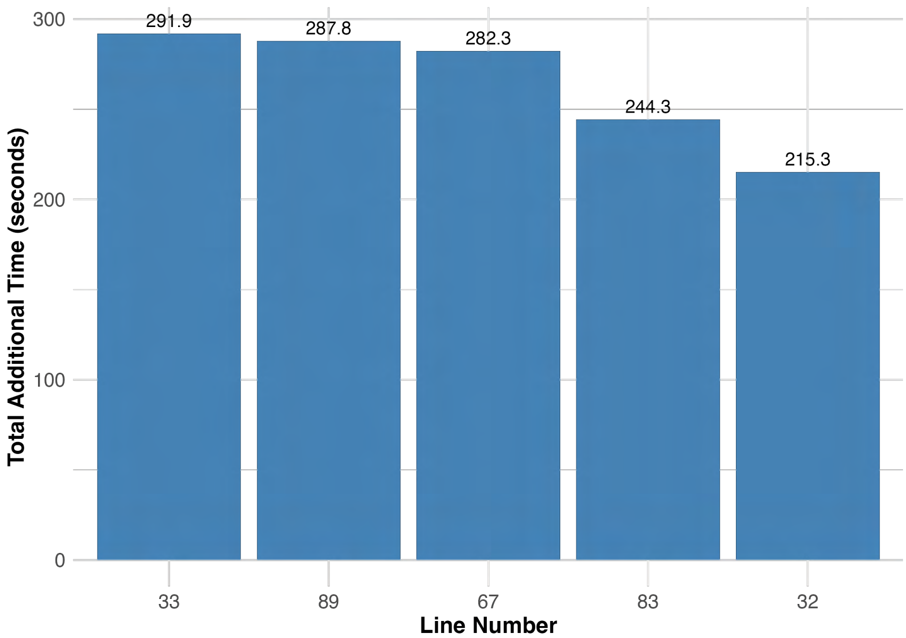



**Figure 5.23:** Bus lines with the highest additional time compared to the median reference period during HVZ2

#### Overview of the Additional Time Needed for Bus Lines in HVZ1 and HVZ2

Table 5.5 presents the additional time (in minutes and seconds) for each bus line during traffic peak hours HVZ1 and HVZ2, as compared to the median reference period.

The range of additional time for bus lines during HVZ1 spans from 0:00 minutes (line 37) to 4min 59s (line 33), reflecting significant variations across the network. Similarly, in HVZ2, the range extends from 0:00 minutes (lines 37, 39 and 42) to 4min 51s minutes (line 33). These ranges indicate that while some lines experience minimal impact from the RNMP, others are substantially affected.

When comparing the two periods, the ranges are relatively similar, with minor shifts in the upper bounds. However, specific lines show notable differences between HVZ1 and HVZ2. For instance, line 83 exhibits a decrease in additional time from 4min 32s minutes in HVZ1 to 4min 04s minutes in HVZ2. Similarly line 72 exhibits a decrease from 2min 28s minutes in HVZ1 to 2min 02s in HVZ2. Conversely, line 89 shows an increase, with additional time rising from 4:36 minutes in HVZ1 to 4:47 minutes in HVZ2.

Overall, the table shows considerable variation in additional time across different bus lines, with some lines experiencing relatively high delays, such as lines 33, 67, and 89, while others remain relatively unaffected, such as lines 37, 39 and 42. These values reveal the differential impact of the RNMP on different bus routes during HVZ1 and HVZ2.

| Line | HVZ1 (min:sec) | HVZ2 (min:sec) |
|---|---|---|
| 31 | 0:46 | 0:42 |
| 32 | 3:30 | 3:35 |
| 33 | 4:59 | 4:51 |
| 35 | 1:35 | 1:32 |
| 37 | 0:00 | 0:00 |
| 38 | 1:55 | 1:52 |
| 39 | 0:01 | 0:00 |
| 40 | 0:28 | 0:27 |
| 42 | 0:01 | 0:00 |
| 46 | 2:24 | 2:24 |
| 61 | 2:29 | 2:28 |
| 62 | 2:34 | 2:33 |
| 64 | 0:32 | 0:30 |
| 66 | 0:15 | 0:15 |
| 67 | 4:48 | 4:42 |
| 69 | 3:29 | 3:22 |
| 70 | 0:33 | 0:34 |
| 72 | 2:28 | 2:02 |
| 73 | 0:30 | 0:23 |
| 75 | 1:27 | 1:28 |
| 76 | 0:26 | 0:18 |
| 77 | 0:25 | 0:26 |
| 78 | 1:31 | 1:31 |
| 80 | 3:27 | 3:19 |
| 83 | 4:32 | 4:04 |
| 89 | 4:36 | 4:47 |
| 99 | 0:06 | 0:06 |

**Table 5.5:** Additional time needed (min:sec) with the RNMP for each bus line in HVZ1 and HVZ2, compared to the median reference period (April–May 2023).

### Overview of the Most Affected Tram Lines

Figures 5.24 and 5.25 illustrate the tram lines with the highest additional time need compared to the median reference period during HVZ1 and HVZ2, respectively.

As shown in Figure 5.24, during HVZ1, tram lines 3, 13, 17, 7, and 15 are most affected. Line 3 has the highest additional time (112.5 seconds), followed by Line 13 (63.4 seconds) and Line 17 (54 seconds). Lines 7 (53 seconds) and 15 (53 seconds) show slightly lower increases in travel time, indicating less significant delays compared to the top three lines.

In HVZ2 (Figure 5.25), the pattern of additional travel time remains largely consistent with HVZ1, with Line 3 still experiencing the highest additional time (112.7 seconds). Similarly, the additional time for Line 13 (63.1 seconds) remains nearly unchanged compared to HVZ1. The additional times for Lines 7 (54.8 seconds), 15 (54.8 seconds), and 17 (53.8 seconds) also show minimal variation, indicating a stable impact of speed reductions across these routes.

The results for HVZ1 and HVZ2 are quite similar for the five most affected tram lines, highlighting a consistent pattern of delays across both periods. However, the ranking of the last three lines (Lines 7, 15, and 17) has slightly changed between HVZ1 and HVZ2.

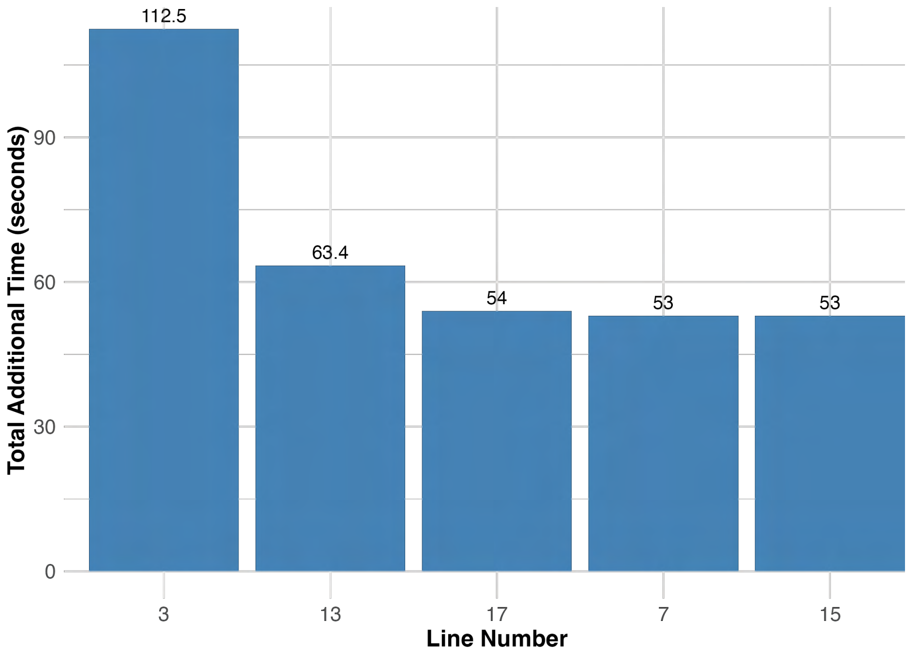



**Figure 5.24:** Tram lines with the highest additional time compared to the median reference period during HVZ1

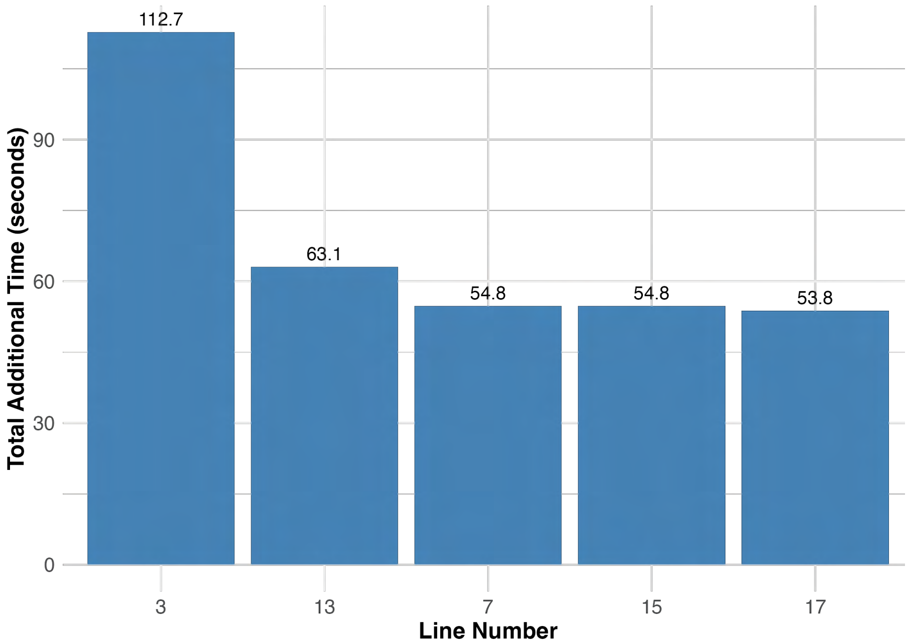



**Figure 5.25:** Tram lines with the highest additional time compared to the median reference period during HVZ2

#### Overview of Additional Time Needed for Each Tram Line during HVZ1 and HVZ2

Table 5.6 presents the additional time needed (in minutes and seconds) for each tram line during HVZ1 and HVZ2.

The range of additional time for tram lines during HVZ1 extends from 0:00 minutes (lines 2 and 11) to 1:52 minutes (line 3), indicating variability in the impact of the RNMP on different tram lines. For HVZ2, the range remains similar, with additional time spanning from 0:00 minutes (lines 2 and 11) to 1:53 minutes (line 3).

The deviations in additional time between HVZ1 and HVZ2 for individual tram lines range from 0:00 minutes to 0:02 minutes, reflecting very minimal differences between the two traffic peak hours. These findings highlight a generally stable pattern of additional time for tram lines between HVZ1 and HVZ2, with only small adjustments observed.

| Line | HVZ1 (min:sec) | HVZ2 (min:sec) |
|---|---|---|
| 2 | 0:00 | 0:00 |
| 3 | 1:52 | 1:53 |
| 4 | 0:08 | 0:08 |
| 5 | 0:31 | 0:31 |
| 6 | 0:28 | 0:28 |
| 7 | 0:53 | 0:55 |
| 8 | 0:23 | 0:25 |
| 9 | 0:24 | 0:25 |
| 10 | 0:01 | 0:01 |
| 11 | 0:00 | 0:00 |
| 13 | 1:03 | 1:03 |
| 14 | 0:31 | 0:33 |
| 15 | 0:53 | 0:55 |
| 17 | 0:54 | 0:54 |

**Table 5.6:** Additional time needed (min:sec) with the RNMP for each tram line in HVZ1 and HVZ2, compared to the median reference period (April–May 2023).

## 5.2 Accessibility Analysis

This section presents the results of the accessibility analysis, evaluating the impact of different stop configurations on pedestrian accessibility in Zurich. The analysis examines how the walking zones ($\leq 2$ min, $2-5$ min, $5-10$ min, and $> 10$ min) around the stops *Löwenbräu* and *Quellenstrasse* vary across the four scenarios mentioned in **??**.

Section 5.2.1 presents visual maps of the walking zones, illustrating the extent of accessibility for each stop while accounting for elevation changes. Section 5.2.2 provides a quantitative comparison, analysing the number of building entrances accessible within each walking zone across the different scenarios.

### 5.2.1 Walking Zones

#### Scenario 1: Baseline

The combined walking zones of the stops *Löwenbräu* and *Quellenstrasse* are shown in Figure 5.26, representing the current situation where both stops are operational. The visualization highlights the extent of the walking zones in the pedestrian network, illustrating accessibility levels when both stops remain in place.


**Figure 5.26:** Walking zones from both stops combined.

#### Scenario 2: Löwenbräu Only

Figure 5.27 illustrates the walking zones for *Löwenbräu* when *Quellenstrasse* is removed. The accessibility zones shift accordingly, expanding the coverage for the remaining stop while increasing walking distances in areas previously served by *Quellenstrasse*.

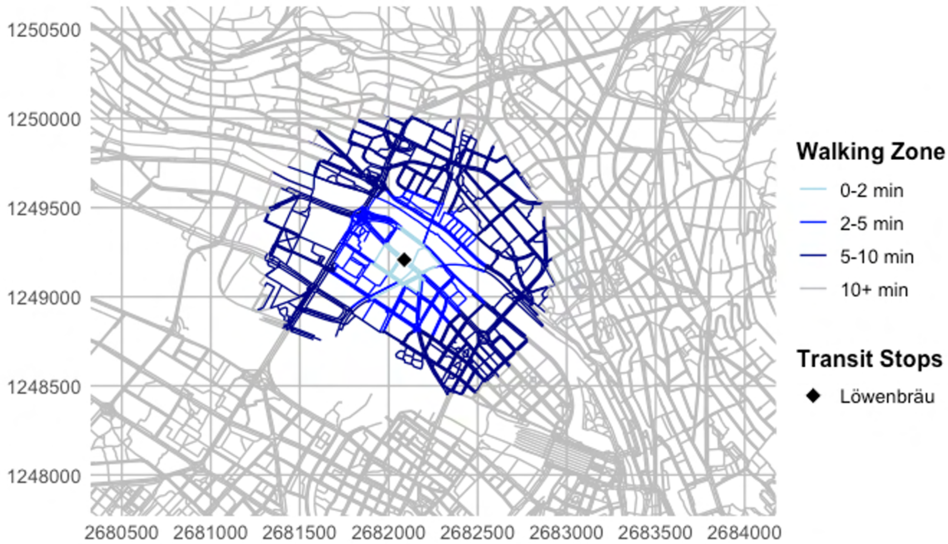



**Figure 5.27:** Walking zones from stop *Löwenbräu*, categorized into walking time classes of 0–2 min, 2–5 min, 5–10 min, and +10 min.

#### Scenario 3: Quellenstrasse Only

Similarly, Figure 5.28 displays the accessibility zones for *Quellenstrasse* when *Löwenbräu* is removed. The impact follows a comparable pattern, with accessibility extending outward from the single remaining stop.


**Figure 5.28:** Walking zones from stop *Quellenstrasse*, categorized into walking time classes of 0–2 min, 2–5 min, 5–10 min, and +10 min.

#### Scenario 4: New Hypothetical Stop

A new hypothetical stop is placed between *Löwenbräu* and *Quellenstrasse*. Figure 5.29 illustrates the walking zones for this new hypothetical stop. [1]

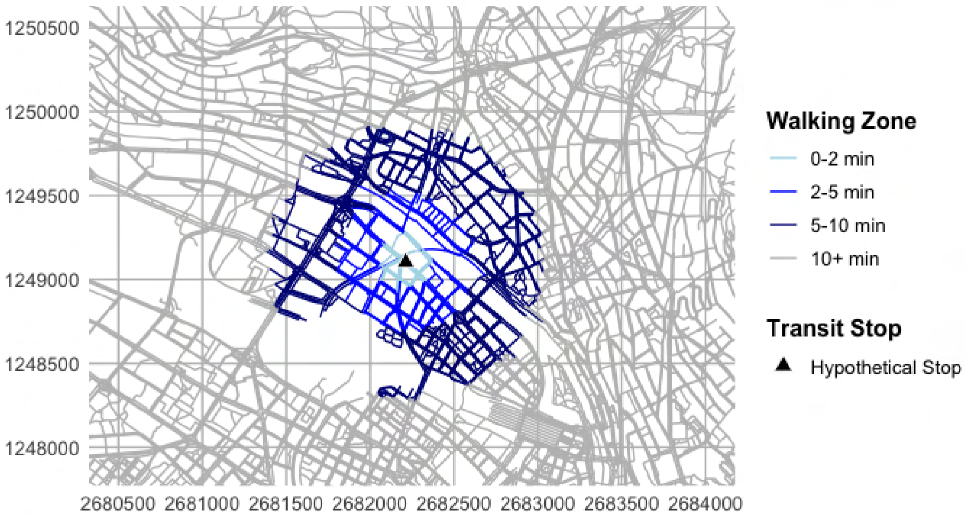



**Figure 5.29:** Walking zones for the hypothetical stop, categorized into walking time classes of 0–2 min, 2–5 min, 5–10 min, and +10 min.

[1] The exact location of the new stop was determined in consultation with VBZ.

### 5.2.2 Quantitative Comparison of Scenarios

Figures 5.30a to 5.30d present a comparative analysis of the distribution of building entrances across the walking zones for the four scenarios. The analysis considers a total of 64,068 building entrances in the City of Zurich, illustrating how the number of entrances within each walking zone ($\leq 2$ min, $2-5$ min, $5-10$ min, and $> 10$ min) varies depending on the stop configuration in each scenario.

#### Scenario 1: Baseline

The baseline scenario (5.30a) shows the accessibility when both stops, *Löwenbräu* and *Quellenstrasse*, are operational. In this scenario:

- **0–2 min zone:** 209 building entrances are accessible.
- **2–5 min zone:** 687 building entrances are accessible.
- **5–10 min zone:** 2,001 building entrances are accessible.
- **10+ min zone:** All other buildings within the city borders (61'171 in total) are lying in a walking distance of more than 10 minutes.

The combined walking zones cover the largest number of building entrances in the 0–2 min and 2–5min $and5--10\,minzone, withrelativelybalancedaccessibilityacrosstheshorterwalkingzones.$

#### Scenario 2: Löwenbräu-Only

The Löwenbräu-only scenario (5.30b) represents accessibility when only the *Löwenbräu* stop remains operational. Results indicate:

- **0–2 min zone:** 93 building entrances are accessible.
- **2–5 min zone:** 494 building entrances are accessible.
- **5–10 min zone:** 1,735 building entrances are accessible.
- **10+ min zone:** All other buildings within the city borders (61'746 in total) are lying in a walking distance of more than 10 minutes.

Accessibility in the 0–2 min and 2–5 min zones is considerably reduced compared to the baseline scenario. However, the 5–10 min zone remains significant, suggesting coverage in the intermediate walking distances.

#### Scenario 3: Quellenstrasse-Only

In the Quellenstrasse-only scenario (5.30c), where only the *Quellenstrasse* stop is operational:

- **0–2 min zone:** 117 building entrances are accessible.
- **2–5 min zone:** 543 building entrances are accessible.
- **5–10 min zone:** 1,751 building entrances are accessible.

- **10+ min zone:** All other buildings within the city borders (61'657 in total) are lying in a walking distance of more than 10 minutes.

This scenario performs slightly better than Scenario 2 Löwenbräu-only in the 0–2 min zone but shows similar results in the 2–5 min and 5–10 min zones.

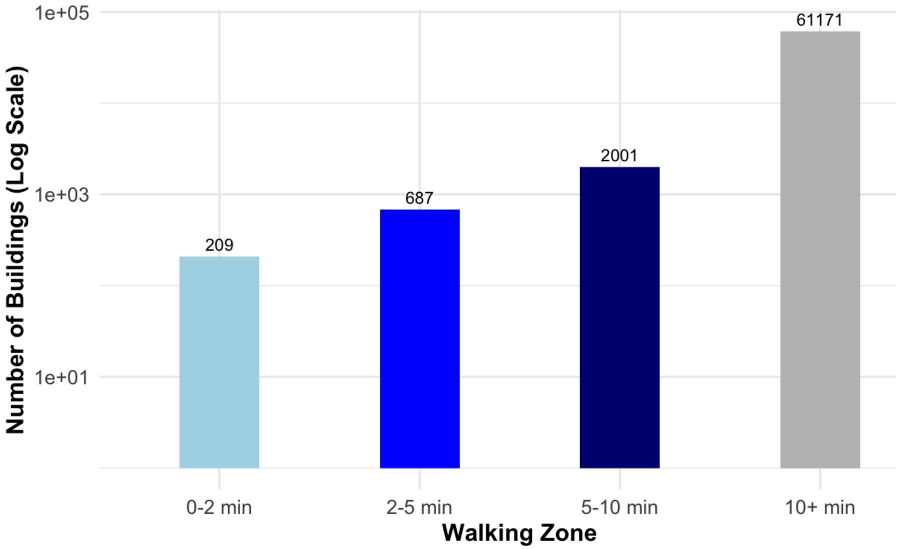
#### Scenario 4: Hypothetical Stop Scenario

The hypothetical stop scenario (5.30d), in which both *Löwenbräu* and *Quellenstrasse* stops are replaced by a new centrally located stop, demonstrates the following results:

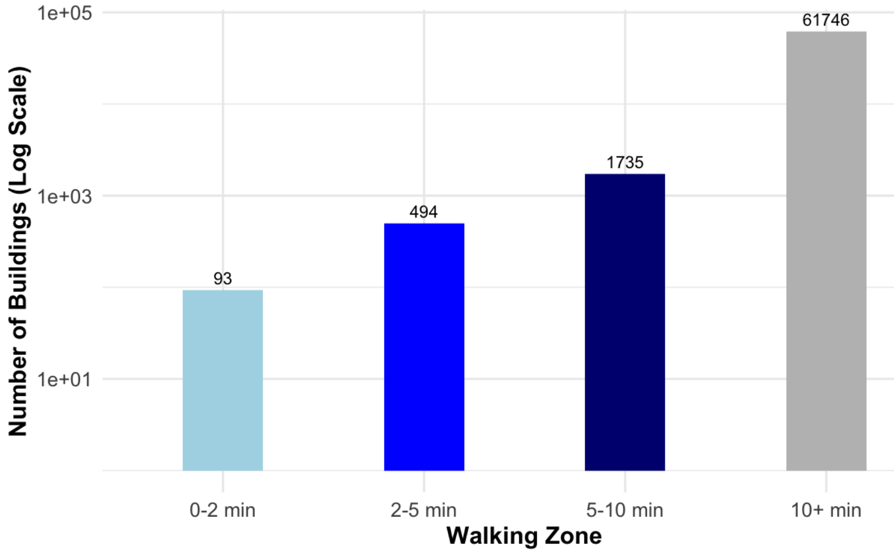
- **0–2 min zone:** 84 building entrances are accessible.
- **2–5 min zone:** 538 building entrances are accessible.
- **5–10 min zone:** 1,703 building entrances are accessible.
- **10+ min zone:** All other buildings within the city borders (61'743 in total) are lying in a walking distance of more than 10 minutes.

The Scenario 4 (Hypothetical scenario) balances accessibility across all walking zones, with results comparable to Scenario 1 (Baseline scenario) in the 2–5 min and 5–10 min zones. However, the accessibility in the shortest walking zone (0–2 min) is even slightly lower than compared to the Scenario 2 (Löwenbräu only).

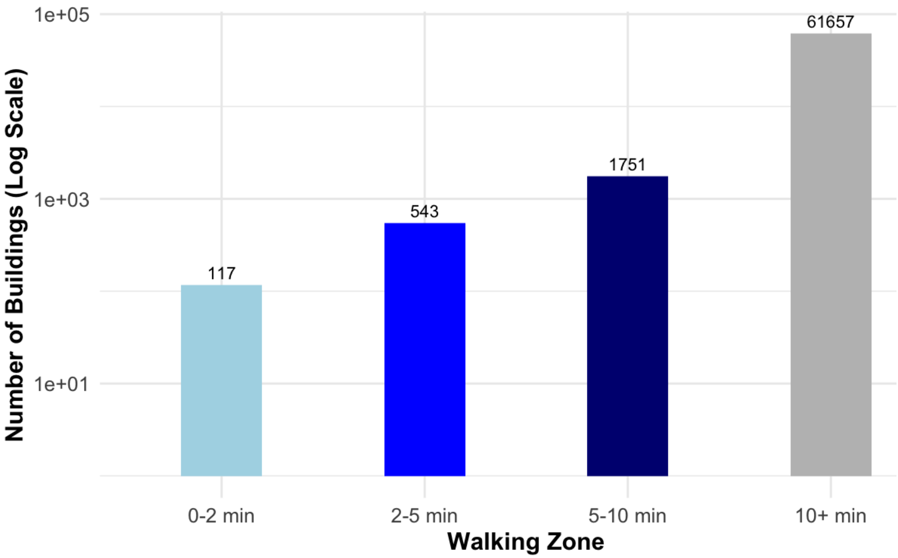
While these results provide a detailed spatial analysis of walking zones, their interpretation and implications will be discussed further in Section 6.1, including considerations of methodological assumptions and potential avenues for future research.



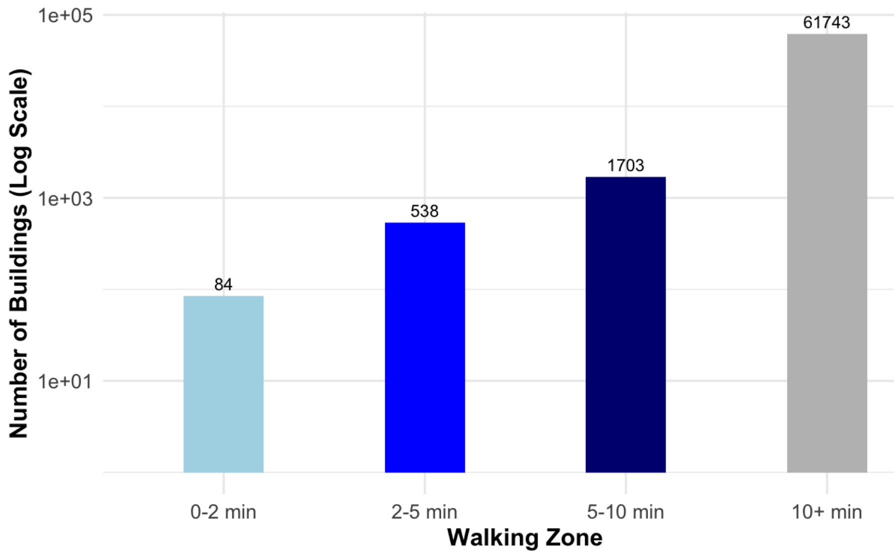

**(a)** Scenario 1: Baseline




**(b)** Scenario 2: Löwenbräu only.




**(c)** Scenario 3: Quellenstrasse only.




**(d)** Scenario 4: Hypothetical stop.

**Figure 5.30:** Number of building entrances accessible in each walking zone for the four analysed scenarios.

# Chapter 6

# Discussion

## 6.1 Results

This Chapter 6 discusses the findings presented in Chapter 5, focusing on the implications of Zurich's RNMP on public transport travel times and accessibility measured in walking distance from the two stops *Löwenbräu* and *Quellenstrasse*. Zurich, with its unique public transport network and specific characteristics, provides a particularly interesting case for such analysis. The methods used in this study were developed in collaboration with VBZ to account for the city's distinctive features, including its reliance on a well-integrated tram and bus system. However, this specificity also means that comparisons to findings from other cities or studies should be approached with caution.

In the initial section of this discussion chapter, Section 6.2 the thesis focuses on Research Objective 1 stated in Section 2.2.4:

**Research Objective 1: Assessing the impact of Zurich's RNMP on public transport travel times**

The objective evaluates how the third phase of Zurich's RNMP—which includes the implementation of 30 km/h speed limits—affects travel times for trams and buses across the network. The speed regimes and travel times under the RNMP are compared with the reference period from April and May 2023, which serves as the pre-implementation baseline. The analysis considers variations between transport mode (tram or bus), direction 1 and 2, and time of day, specifically focusing on HVZ1 and HVZ2. The study aims to quantify additional travel time needs, identify their locations, and evaluate variations throughout the network, while also pinpointing individual lines that are most significantly affected under these conditions.

## 6.2 Effects of the RNMP

### 6.2.1 Statistical Analysis over entire network

#### Comparison of results between HVZ's of entire bus network

The implementation of the RNMP resulted in an increased travel times across the entire bus network. The total median additional time increased up to 32:09 minutes, with the Q3 additional time rising to 49:01 minutes. When comparing HVZ1 and HVZ2, the median additional time increased slightly from 31:31 minutes in HVZ1 to 32:09 minutes in HVZ2 (Table 5.2), while the Q3 additional time rose from 47:42 minutes in HVZ1 to 49:01 minutes in HVZ2. These marginal differences indicate that the RNMP's impact on travel times is consistent across both peak traffic periods, with only minor variations observed (Table 5.1).

The most significant impacts of the RNMP on additional median travel time occur in areas where buses, during the reference period before the implementation of the RNMP, were able to achieve higher speeds due to favorable traffic conditions and larger stop distances (Verkehrs-Club der Schweiz (VCS), 2023). In these segments, the reduction in speed limits has a more pronounced effect, as vehicles that could previously operate at higher speeds must now adhere to lower regulated limits.

This consistency in additional travel times between HVZ1 and HVZ2 is striking, especially considering that peak-hour traffic conditions are typically characterized by high congestion, frequent stops, and reduced travel speeds. The fact that travel time losses remain similar across both peak periods suggests that speed reductions such as *Tempo 30* do not have a disproportionately high impact during these times.

Interestingly, when comparing these results for HVZ1 and HVZ2 with studies that analyzed additional travel time needs outside peak hours, the increase in travel time appears to be more pronounced. During off-peak periods, when traffic volumes are lower, public transport vehicles can generally reach higher speeds (VBZ, 2024). In such cases, a reduction in the speed limit has a greater relative effect on overall travel times. A study by Metron Verkehrsplanung AG on behalf of the Verkehrs-Club der Schweiz (VCS) supports this interpretation. It found that public transport vehicles, particularly buses and trams, frequently operate below posted speed limits during peak hours due to frequent stops and interactions with other traffic. As a result, speed reductions like *Tempo 30* tend to have a smaller impact on travel times during peak hours than might be expected (Metron, 1994; Verkehrs-Club der Schweiz (VCS), 2023). Additionally, internal studies conducted by VBZ across different lines revealed almost similar travel time impacts in HVZ1 and HVZ2, further reinforcing this observation (VBZ, 2024).

The analysis of mean additional time per 100 meters over the entire bus network further corroborates these findings. The differences between HVZ1 and HVZ2 are minimal, ranging from 0.54 seconds (HVZ2 Dir2) to 0.58 seconds (HVZ2 Dir1). These values align with the literature on additional time caused by 30km/h speed limits, where times range between 0.4 and 2.7 seconds per 100 meters, with an average of 1.5 seconds and a standard deviation of 0.6 seconds (Eckart et al., 2018; VBZ, 2019; Metron, 1994; Dittmann, 2013; Verkehrs-Club der Schweiz (VCS), 2023). The slightly lower values observed in this study (e.g., on average 0.56 seconds/100m) can be attributed to the network-wide scope of the analysis, which includes many segments where the speed regime will not change. Unlike previous studies mentioned above, which have focused primarily on individual street segments or specific areas where *Tempo 30* is widely introduced, this research analyses the entire Zurich public transport network. As a result, the inclusion of unaffected or minimally impacted segments lowers the overall averages.

#### Comparison of results between Direction 1 and 2 entire bus network

It is important to note that the assignment of Directions 1 and 2 does not inherently correspond to outbound or inbound journeys. The distinction between the two was introduced in this study primarily to enhance the clarity of segment visualization. In certain sections where multiple bus lines operate, the designated Direction 1 for one line may run in the opposite direction of another line's designated Direction 1. As a result, the direction labels do not represent a consistent classification of travel flow across the network.

Nevertheless, when analysing each direction separately, a consistent trend emerges. In HVZ1, the median additional times for Directions 1 and 2 are 15:19 minutes and 16:12 minutes, respectively, while in HVZ2, they are 16:50 minutes and 15:19 minutes. The Q3 additional time follows a similar pattern, showing slightly higher values in HVZ2 for both directions.

The differences between the two directions are minimal, which aligns with the implementation of the RNMP. The speed regulations introduced as part of the RNMP apply uniformly to both sides of the road, ensuring that the same speed limit is enforced regardless of direction. As a result, similar additional travel times were anticipated in both directions, reflecting the symmetry in the application of the speed regime on both sides of the street (Stadt Zurich, 2021b).

#### Comparison of results between HVZ's entire tram network

As the documentation of the effects of speed reductions on trams is limited in the literature, the comparison to existing studies is made in a holistic manner.

The additional travel times for the tram network during HVZ1 and HVZ2 show some variations, though the overall differences remain relatively small and similar as compared to the results for buses mentioned in Section 5.1.1. The median additional time in HVZ1 ranges from 2:10 minutes (Dir2) to 2:19 minutes (Dir1), whereas in HVZ2, it ranges from 2:14 minutes (Dir1) to 2:47 minutes (Dir2). This indicates a slight increase in median additional time in HVZ2 for Direction 2, while Direction 1 remains relatively stable across both periods.

The Q3 additional time shows more variation between HVZ1 and HVZ2. For HVZ1, the Q3 values range from 4:00 minutes (Dir1) to 5:06 minutes (Dir2), while in HVZ2, they range from 3:51 minutes (Dir1) to 5:23 minutes (Dir2). Notably, Direction 1 experiences a slight decrease in Q3 time from HVZ1 to HVZ2, while Direction 2 shows a small increase, similar to the bus results 6.2.1.

#### Comparison of results between Direction 1 and 2 entire tram network

There are minimal differences observed between Direction 1 and Direction 2 in additional travel times. For instance, the median additional time in HVZ1 is slightly higher for Direction 1 (2:19 minutes) compared to Direction 2 (2:10 minutes), as shown in Table 5.3. However, during HVZ2, Direction 2 experiences a more pronounced increase, with median additional times rising to 2:47 minutes, compared to 2:14 minutes for Direction 1.

Similarly, the Q3 additional time in HVZ1 is lower for Direction 1 (4:00 minutes) than Direction 2 (5:06 minutes), but in HVZ2, the Q3 values increase for Direction 2 to 5:23 minutes, while Direction 1 slightly decreases to 3:51 minutes (Table 5.3). The results for buses and trams show minimal deviations when comparing Direction 1 with Direction 2 in each HVZ.

#### Comparison of results over entire bus and tram network

The implementation of speed reductions as part of the RNMP has shown notable impacts on public transport travel times, particularly for buses (see Table 5.1 and 5.3). The analysis indicates that buses are more significantly affected than trams, as evidenced by higher median additional travel times and Q3 values during HVZ1 and HVZ2.

When comparing the mean additional time per 100 meters, the values for buses (0.54 to 0.58 seconds) align well with ranges reported in existing literature (Metron, 1994; Eckart et al., 2018), which observed values between 0.4 and 2.7 seconds per 100 meters. However, the mean additional time for trams (0.019 to 0.022 seconds) is significantly lower than what is typically reported in the literature.

The higher additional time need for buses can be attributed to three main factors:

1. **Independent rail bodies (UBK):** Unlike trams, buses do not operate on independent rail bodies and are instead subject to mixed-traffic conditions. As a result, they are more directly impacted by speed limitations and traffic conditions such as congestion and delays at intersections (Baker and Uhler, 2022).

2. **Retention of 50 km/h on specific tram segments:** Another reason for the lower impact on trams is that several tram corridors were exempted from the *Tempo 30* regulation and retained a 50 km/h speed limit during daytime, as specified in the speed regulation plan. In contrast, such exemptions are far less common within the bus network, meaning that buses are more consistently subjected to the reduced speed limit across their entire route (Stadt Zurich, 2021b).

3. **Operational speeds defined in traffic models:** According to VBZ traffic models, the operational speed under a 30 km/h speed limit is set at 27 km/h for buses and 29 km/h for trams, values that were also applied in this study [1] (VBZ, 2024). This difference in operational speeds reflects the ability of trams to maintain more consistent speeds across the network, primarily due to their independent tracks. Furthermore, trams are equipped with speed regulators, which enable them to sustain a stable speed profile, unlike buses, which are more affected by traffic conditions and stops. As a result, the slightly lower operational speed for buses contributes to their higher additional travel time.

The 2 km/h difference in operational speeds between buses and trams may appear minimal but has a tangible effect on travel times. For example, over a 100 m segment, this difference results

[1] Values discussed in consultation with VBZ during discussions in February 2024.

in an additional time of approximately 1.8 seconds for buses compared to trams. While this impact is relatively small for short distances, it can accumulate significantly over longer segments or across the entire network, and thus could also affect the different results for buses and trams. For segments where the previous speed limit was 50 km/h and has now been reduced to 30 km/h, this time difference further highlights the sensitivity of buses to the new speed regime.

Overall, the results demonstrate that the implementation of the RNMP disproportionately affects buses due to their lack of UBK, more bus routes affected overall, and lower operational speeds. In contrast, trams are better equipped to mitigate the effects of reduced speed limits, although slower operational speeds and potential stop-related delays still contribute to increases in time need compared to the reference period.

#### Hotspot analysis entire network

The hotspot analysis, illustrated in Figures 5.18b, 5.19, 5.20b, and 5.21, identifies areas within the network where the effects of the Road Noise Mitigation Plan are most pronounced. The results closely align with the findings of the statistical analysis, confirming that buses are more significantly impacted by speed reductions compared to trams. This is evidenced by the generally higher Gi* Z-scores for buses, indicating more substantial travel time delays.

The observed Z-scores reveal localized hotspots characterized by disproportionately high additional travel times compared to their surrounding areas. For buses, Z-scores exceed 15 in certain segments, while for trams, the highest Z-scores mainly range from 10 to 12. These elevated Z-scores indicate that specific areas experience significant addtional time needs, which are prominent against the broader network, where many segments exhibit minimal or no additional travel time impacts, as can be seen in the results of the detailed analysis in Section 5.1.5.

The spatial distribution of hotspots is primarily concentrated in central urban areas, where public transport routes converge and interactions with other modes of traffic are frequent. These localized hotspots are likely influenced by factors such as passenger boarding times, shared road spaces, and signalized intersections. Such factors exacerbate delays in specific areas while leaving other segments of the network relatively unaffected.

The lower Z-scores for trams compared to buses indicate their reduced sensitivity to the RNMP, as trams benefit from independent rail bodies (UBK) that minimize their exposure to changes in speed regimes. This structural advantage enables trams to maintain more stable travel times, even in areas where speed reductions occur.

### 6.2.2 Statistical Analysis over separate bus lines

The additional travel times observed in this study are particularly relevant when analysing their effect on turnaround times, which are critical for public transport operations. Turnaround times are influenced by several factors, including maximum achievable speeds, and are a key component of the total cycle time, which includes travel times from point A to point B and back, as well as stop times and operational buffers. Insufficient turnaround times can disrupt schedules, leading to delays and instability in operations (Verkehrs-Club der Schweiz (VCS), 2023). Therefore, a detailed analysis of line-specific impacts was conducted to identify the routes most affected by the RNMP.

The analysis of additional travel times for individual bus lines highlights significant variations in how the Road Noise Mitigation Plan affects operations. Figures 5.22 and 5.23, along with Table 5.5, provide a comprehensive overview of these impacts during HVZ1 and HVZ2. Therefore, the results of this study for lines 33 and 77 can be compared to a VBZ study, which also analysed the impacts of speed limits of 30km/h in HVZ1 and HVZ2 on these certain bus lines.

Line 33 consistently exhibits the highest additional time among all bus lines, with 4:59 minutes in HVZ1 and 4:51 minutes in HVZ2, as shown in Table 5.5. These results are slightly lower than the findings reported by VBZ (2024), where line 33 experienced additional travel times of 5:51 minutes (351 seconds) in both HVZ1 and HVZ2 under *Tempo 30* conditions. This is due to the different reference periods used, and the VBZ analysis already includes timetables from 2026, accounting for slight differences in overall travel time.

Notably, both the VBZ (2024) analysis and this study confirm minimal differences in the additional time impacts of *Tempo 30* between HVZ1 and HVZ2. This consistency reinforces the finding that *Tempo 30* affects public transport operations similarly across both peak periods (VBZ, 2024).

In addition to line 33, this study identified four other bus lines with significant additional travel times: lines 67, 89, 83, and 72. These lines exhibit substantial delays during both HVZ1 and HVZ2, as shown in Table 6.1.

| **Line** | **HVZ1 (min:sec)** | **HVZ2 (min:sec)** |
|---|---|---|
| 33 | 4:59 | 4:51 |
| 67 | 4:48 | 4:42 |
| 89 | 4:36 | 4:47 |
| 83 | 4:32 | 4:04 |
| 72 | 2:28 | 2:02 |

**Table 6.1:** Additional travel time for most affected bus lines in HVZ1 and HVZ2.

While line 33 demonstrates the highest delays overall, these four lines also fall within the range of significant impacts due to *Tempo 30*. The relatively high time losses for these lines suggest that a more detailed, line-specific analysis would be necessary to assess the operational consequences and potential mitigations.

A VBZ (2024) analysis also noted substantial delays during off-peak periods (RVZ), which were not part of this study, where line 33 experienced time losses of up to 8:23 minutes (503 seconds). These delays during RVZ require an increase in vehicle deployment, with the number of required vehicles rising from 13 to 14 during HVZ2. This operational adjustment would result in additional annual costs of CHF 300,000, assuming *Tempo 30* is implemented on Triemlistrasse and Letzigraben, and the required vehicle is available. Without this additional vehicle, similar increases in vehicle needs could extend to HVZ1 and NVZ, further increasing annual costs by CHF 530,000 (VBZ, 2024). High additional travel times on these lines could potentially affect turnaround times, which play a critical role in public transport scheduling and stability. Insufficient turnaround times may require operational adjustments, such as:

1. **Deployment of Additional Vehicles:** To maintain current service frequencies, the introduction of extra vehicles might be necessary. This could lead to higher operational costs, as observed in the VBZ analysis for line 33, where an additional vehicle was required during HVZ2 (Verkehrs-Club der Schweiz (VCS), 2023; VBZ, 2024).

2. **Increased Staffing Requirements:** If additional vehicles are deployed, corresponding increases in driver schedules and personnel resources would be needed (Verkehrs-Club der Schweiz (VCS), 2023; VBZ, 2024).

3. **Revisions to Timetables:** To account for the delays caused by *Tempo 30*, modifications to timetables may be required, potentially impacting passenger connections and overall service quality (Verkehrs-Club der Schweiz (VCS), 2023; VBZ, 2024) [2].

Given the significant impacts observed on lines 67, 89, 83, and 72, these routes warrant further analysis to evaluate how *Tempo 30* affects their turnaround times. Detailed studies should investigate whether additional vehicles, personnel, or timetable adjustments are necessary to maintain operational efficiency. For example, similar to the VBZ findings for line 33, high delays could lead to the need for additional vehicles during peak hours, incurring higher operational costs.

This study reveals minimal differences in additional travel times for bus line 77 between HVZ1 and HVZ2, with 0:25 minutes in HVZ1 and 0:26 minutes in HVZ2. These findings align closely with the VBZ analysis, which also observed minimal effects of 8 seconds additonal time need for HVZ1 and HVZ2 on this line. According to VBZ (2024), the turnaround time for line 77 without *Tempo 30* was reported as 4:50 minutes (290 seconds) in HVZ1 and 4:35 minutes (275 seconds) in HVZ2. With *Tempo 30*, these values decreased slightly to 4:42 minutes (282 seconds) in HVZ1 and 4:27 minutes (267 seconds) in HVZ2. These changes indicate that *Tempo 30* has only a minor effect on the turnaround time for this line. This finding is consistent with the minimal differences in additional travel times observed in this study, further supporting the observation that *Tempo 30* results in comparable impacts across HVZ1 and HVZ2 for this line. Moreover, VBZ concluded that no additional vehicles were required for line 77, even with the implementation of *Tempo 30* (VBZ, 2024).

### 6.2.3 Statistical Analysis over separate tram lines

The analysis of tram lines under the Road Noise Mitigation Plan indicates that additional travel times are consistently minor when compared to buses. Despite the overall stability, some tram lines exhibit slightly higher delays than others. Line 3 consistently experiences the longest additional time, averaging between 1:52 and 1:53, followed by Line 7 (0:53–0:55), Line 13 (1:03), and Line 15 (0:53–0:55). These lines frequently operate in central or high-traffic areas, where interactions with other vehicles and passengers may contribute to increased delays. Nevertheless, even for these lines, the additional wait times remain significantly lower than those observed for

[2] Discussion with VBZ experts, December 2024.

buses, underscoring the limited impact of the RNMP on tram operations.

The additional travel times for tram lines shown in Table 5.3 are remarkably stable across HVZ1 and HVZ2. The differences between the two periods are minimal, with deviations ranging from 0:00 minutes to 0:02 minutes. For example, Line 3—the most affected tram line—exhibits an increase of only one second between HVZ1 and HVZ2. Similarly, Lines 7, 8, and 15 demonstrate small increases of one to two seconds, while the remaining lines maintain consistent travel times across both traffic periods.

This stability aligns with the design of Zurich's tram network, which benefits from UBK resulting in fewer interactions with road traffic compared to buses. These factors enable trams to maintain a consistent operational profile, even under the RNMP.

Unlike buses, where previous studies have documented the impact of speed limits on travel times, comparable studies on trams are scarce. Most existing research focuses on buses due to their greater interaction with road traffic. However, the findings of this study highlight that the effects of the RNMP on trams are minimal and localized, emphasizing the infrastructural advantages of trams in urban transport systems. The minimal additional travel times observed for trams indicate that the RNMP does not significantly disrupt tram operations. Turnaround times remain largely unaffected, thus no extra vehicles or staffing will be required to maintain current service levels. This stands in stark contrast to buses, where operational adjustments may be necessary for certain lines experiencing higher delays.

However, for lines 3 and 13, which exhibit slightly higher additional travel times, localized interventions such as UBK evaluations or schedule adjustments could further reduce delays. These measures would ensure that even minor disruptions are addressed proactively, to maintaining Zurich's high standards for public transport efficiency.

#### Impact of stop spacing on RNMP effects

Stop spacing plays a critical role in the effects of the RNMP, as longer distances between stops allow vehicles to accelerate and approach their maximum speeds. Consequently, *Tempo 30* has a greater impact on routes with longer stop distances, where reduced speed limits significantly increase travel times.

Literature highlights that travel times are influenced by stop spacing, dwell times, and maximum allowable speeds. Larger stop spacing reduces required travel time for every 100 meters, while shorter spacing naturally limits operational speeds and minimizes the impact of *Tempo 30* (Verkehrs-Club der Schweiz (VCS), 2023; Eckart et al., 2018).

This trade-off is evident in the results of this analysis, particularly in segments with longer distances between bus stops, such as between *Waidspital* and *Weihersteig* or *Lägernstrasse* and *Rotbuchstrasse*. In these areas, vehicles cannot fully utilize their acceleration potential, amplifying the travel time losses caused by *Tempo 30*. Conversely, shorter stop distances mitigate these effects by naturally constraining speed.

These findings underscore the need to consider stop spacing when assessing the RNMP's impacts. Mitigation strategies such as optimizing traffic signal timings and adjusting schedules could help reduce travel time losses on routes with longer stop distances.

#### General Impacts of the RNMP

The consequences of implementing *Tempo 30* can range from no noticeable impact to minor adjustments in departure times, and in rare cases, the deployment of additional buses or entirely new service concepts. The latter is only applied in exceptional circumstances where time buffers are minimal, and no possibilities for bus prioritization exist (Kanton Luzern, 2024).

The impact of the additional time need related to the RNMP varies significantly across bus and tram lines due to differences in their operational characteristics and timetables. Certain lines, such as line 33 and its closely linked lines 72, 83, and 89, require synchronized schedules to ensure coordinated operations in shared sections. The introduction of *Tempo 30* on these lines requires a complete revision of their timetables to maintain regular intervals, potentially leading to additional operational costs (VBZ, 2024).

It cannot be universally determined at what level of additional time *Tempo 30* generate, cause increased costs. Each line must be evaluated individually, as the effects depend on factors such as the available turnaround time reserves and the line's timetable structure. Lines with tight schedules and limited buffer times are more likely to require adjustments, such as additional vehicles, personnel, or timetable changes, to absorb delays (VBZ, 2024).

#### Mitigation Strategies and Policy Implications

To minimize the impact of *Tempo 30* on public transport, targeted interventions such as optimizing traffic signal timings, improving passenger flow management, and expanding dedicated tram-priority lanes can help reduce delays and ensure operational efficiency as found in the literature (Verkehrs-Club der Schweiz (VCS), 2023; SVI, 2021; Eckart et al., 2018). These strategies should be tailored to the specific needs of each network or line, particularly for routes experiencing higher additional travel times.

However, in the case of Zurich, the potential for further prioritization at traffic signals is already largely exhausted. Many intersections are already optimized to prioritize trams and buses, limiting the scope for additional improvements in signal control. In contrast, other cities may have greater potential for signal prioritization to mitigate *Tempo 30*-related delays[3].

The findings also highlight the broader policy challenge of balancing increased travel times with urban mobility goals, such as reducing car dependency and promoting sustainable transportation. Measures such as revising stop locations, adjusting schedules, and conducting localized analyses of high-impact segments could help address these challenges while maintaining public transport reliability. Additionally, the relatively lower impact of Tempo 30 on trams underscores the potential benefits of expanding dedicated infrastructure to enhance resilience and efficiency in public transport systems. It further emphasizes the need for a city- and network-specific approach when assessing the effects of Tempo 30 on public transport. Each city and its public transport system must be analysed individually to determine how best to mitigate potential impacts. As demonstrated in the case of Zurich, existing infrastructure, signal prioritization,

[3] Based on discussions with VBZ experts, January 2025.

and urban characteristics play a crucial role in shaping the extent of Tempo 30's effects and the feasibility of mitigation measures.

## 6.3 Accessibility Analysis

This section of the discussion addresses Research Objective 2 stated in Section 2.2.4:

Research Goal: Analysing the effects of stop adjustments on accessibility.

This research objective evaluates the effects of stop removal or relocation, focusing on how increased distances between public transport stops influence accessibility. A detailed case study is conducted for the stops *Löwenbräu* and *Quellenstrasse*, assessing the impact on walking distances for residents and exploring the potential benefits for public transport travel times. These adjustments are considered in the context of this study as a possible measure to compensate for travel time losses caused by the implementation of the 30 km/h speed limit, balancing network efficiency with accessibility for the affected population. Four scenarios are analysed to evaluate different approaches to stop consolidation and their respective impacts on accessibility. The results presented in this section are based on the analysis conducted in Chapter 5.

The accessibility analysis highlights the significant influence of stop configurations on pedestrian access, as demonstrated in the *Löwenbräu* and *Quellenstrasse* case study. Scenarios involving stop removal or consolidation indicate how these changes affect walking times for the surrounding population These insights provide valuable guidance for public transport operators in understanding the correlation between stop spacing and accessibility within Zurich. Each stop configuration scenario presents unique advantages and disadvantages, with important implications for both pedestrian accessibility and public transport efficiency, as discussed below.

#### Scenario 1: Baseline

The baseline scenario, where both *Löwenbräu* and *Quellenstrasse* stops remain operational, provides the highest accessibility. It ensures the largest number of building entrances are accessible in the 0–$\leq$2 min (209 entrances) and 2–$\leq$5 min (687 entrances) walking zones. This configuration is ideal for maximizing accessibility and equity. However, frequent stops can reduce operational efficiency by increasing travel times for public transport vehicles.

#### Scenario 2: Löwenbräu-Only and Scenario 3: Quellenstrasse-Only

Both removal scenarios result in reduced accessibility compared to Scenario 1, particularly in the 0–$\leq$2 min zone, with 93 and 117 building entrances remain accessible in each case. While these scenarios may enhance operational efficiency by reducing the number of stops, they disproportionately affect residents near the removed stops, potentially discouraging public transport use and raising equity concerns. However, it is also important to consider the benefits for through-traveling passengers. The removal of one of the two stops would lead to a reduction in total travel time for those remaining on board, as fewer stops mean fewer interruptions and a smoother journey. This trade-off between accessibility and travel time efficiency highlights the complexity of stop consolidation decisions and the need for a balanced approach that considers both local accessibility and network-wide service optimization [4].

#### Scenario 4: Hypothetical Stop Scenario

The hypothetical stop scenario, where both stops are replaced with a single centrally located stop, offers a compromise between accessibility and operational efficiency. While it balances accessibility across the 2–≤5 min and 5–≤10 min zones, it results in the lowest accessibility in the 0–≤2 min zone (84 building entrances). This trade-off highlights the challenges of centralizing stop locations without disadvantaging nearby residents.

#### General Implications for *Tempo 30* segments

The introduction of *Tempo 30* segments complicates the balancing of stop accessibility and operational efficiency. Longer travel times caused by reduced speed limits may be partially mitigated by stop modifications, particularly in areas with closely spaced stops, such as *Löwenbräu* and *Quellenstrasse*. However, the effectiveness of these adjustments depends on line-specific factors, such as:

- Whether additional vehicles are required to maintain service frequency.
- How timetable adjustments align with operational goals and passenger needs.
- The interdependence of stops on the same or overlapping routes.

Stop modifications could provide an opportunity to offset travel time losses for lines most affected by the RNMP. However, such changes require careful evaluation to ensure that they do not disproportionately reduce accessibility or service quality for Zurich's population.

Thereby one has to mention that stop removals or relocation are challenging to implement due to several factors. Political opposition is a common obstacle, as such changes often face opposition from residents and stakeholders who perceive them as a reduction in service quality[5]. Additionally, identifying suitable locations for new stops is particularly difficult in dense urban areas, where space is limited, traffic flow must be maintained, and stop locations must meet criteria for accessibility, safety, and integration into the overall public transport network (Stadt Zurich Tiefbauamt, 2024). These complexities highlight the need for thorough planning, stakeholder participation, and detailed cost-benefit assessments to ensure successful implementation.

## 6.4 Limitations

### 6.4.1 Effects of the RNMP

The calculations in this analysis are based on a two-month reference period, spanning from April 1 to May 31, 2023. This period was selected as it is representative of typical network conditions throughout the year, providing a reliable baseline for the study. However, isolated incidents during this timeframe may still have influenced the results. Additionally, while this period captures average conditions, it does not account for broader temporal variations, such as

[4] Personal communication with VBZ experts
[5] Discussion with VBZ experts, August 2024.

seasonal changes in weather, fluctuations in tourism, or variations in commuting patterns, all of which could significantly impact traffic conditions and public transport efficiency.

The use of 20-meter segments as the smallest unit of analysis allows for detailed spatial insights but introduces a degree of generalization. This approach may smooth out localized variations, such as short-term congestion or vehicle interactions, and may not fully capture specific traffic dynamics within individual segments. Similarly, the study assumes that vehicles uniformly comply with the 30 km/h speed limit, which may not reflect real-world behaviour where driver non-compliance or uneven adherence could alter the results.

The analysis focuses solely on the reduction in speed limits as the primary determinant of travel time losses, excluding additional traffic calming measures, such as chicanes or narrowing of the roads, which are often implemented along with speed reductions to improve safety. These measures could amplify delays beyond the estimates presented in this study. Furthermore, potential adjustments to traffic priority rules, such as changes to transit signal priority at intersections, were not included. If such rules were modified to deprioritize public transport, it could lead to additional delays for public transport vehicles.

Behavioural responses to *Tempo 30*, such as shifts in travel mode, were not included in this analysis. For instance, some individuals may switch from public transport to private vehicles, bicycles, or walking if they perceive public transport as less efficient due to increased travel times. Additionally, reduced speeds may create safer traffic conditions, encouraging greater use of active modes like walking and cycling. While this could reduce public transport ridership and impact operational planning and cost efficiency, it may also support broader sustainability goals. Furthermore, the analysis does not account for potential reductions in motorized individual vehicle (MIV) traffic on certain streets as a result of *Tempo 30*. Streets with lower traffic volumes may benefit from reduced congestion and shorter delays, partially offsetting the impacts of speed reductions, whereas high-traffic streets may experience amplified delays. These factors highlight the complex and context-dependent implications of *Tempo 30* on urban mobility systems.

Finally, the study does not incorporate network-wide traffic dynamics or the ripple effects of *Tempo 30* on adjacent road segments. Public transport lines often depend on interlinked routes, and the exclusion of these interactions may limit the broader applicability of the findings.

### 6.4.2 Accessibility Analysis

The accessibility analysis conducted in this thesis also has certain limitations. First, the analysis adopts a simplified approach that measures the proximity of stations to households, without considering passengers' personal preferences. This approach assumes that users always select the nearest stop, which may not accurately reflect real-world behavior, where travel decisions are influenced by factors such as route convenience, transfer opportunities, or service frequency.

Second, socio-economic and demographic variables, such as income levels, car ownership, and age distribution, were not included. While incorporating these variables could provide valuable insights into equity impacts, they were excluded to reduce uncertainty and focus on stable and measurable factors. However, these factors are likely to fluctuate over the next few years as the RNMP is phased in, which could affect accessibility outcomes.

Third, the analysis assumes uniform walking speeds across individuals, with adjustments made only for elevation. This oversimplifies the diversity of walking behavior, particularly for individuals with mobility impairments or varying physical abilities. Accounting for such variations would provide a more realistic representation of accessibility.

The analysis also focuses solely on spatial accessibility and does not evaluate operational factors such as service frequency, travel times, or the quality of transfers. While this approach provides a detailed understanding of walking accessibility to the stop, it does not fully capture the overall quality of public transport services.

# Chapter 7

# Conclusion

## 7.1 Contributions

This master's thesis provides several contributions to the analysis of Zurich's Road Noise Mitigation Plan (RNMP) and its implications for public transport operations as well as to understanding the interplay between stop removal or relocation and accessibility. The most significant contributions are summarized below:

1. **Quantitative Analysis of *Tempo 30* Impacts:** The study offers a comprehensive, data-driven evaluation of the effects of Zurich's RNMP on public transport travel times. It investigates the relationship between speed limitations and their effects on public transport, particularly in the context of reducing street noise. By analysing buses and trams across the entire network, it identifies specific patterns of additional time need and provides a clear distinction between the impacts on the two transport modes.

2. **RNMP Effects on Tram vs. Buses:** The study results reveal that the effects of the RNMP on buses are significantly greater than those on trams. This can be attributed to three main factors. First, trams operate on independent rail bodies (UBK) in several parts of the network, exempting them from the introduced speed limits with the RNMP. Second, some tram corridors retain a 50 km/h speed limit in the RNMP during the day, whereas such exemptions are much less common in the bus network. Third, trams benefit from a slightly higher operational speed under Tempo 30 (29 km/h vs. 27 km/h for buses) in traffic models, as well as speed regulators that allow them to maintain a more stable speed profile.

3. **Comparison between HVZ1 and HVZ2:** The comparison of results for HVZ1 and HVZ2 reveals minimal deviations between peak traffic hours, a finding that aligns with previous analyses conducted by VBZ for several lines, further validating the consistency of the observed patterns (VBZ, 2024).

4. **Line-Specific Insights:** This study, being the first to analyse the network across the complete city of Zurich, highlights significant variations in the impact of *Tempo 30* across individual lines, identifying bus lines like 33, 72, 83, and 89 as particularly affected. It emphasizes the need for line-specific timetable adjustments and operational strategies to mitigate delays.

5. **Policy- and Urban Design Relevant Findings:** This thesis provides valuable evidence for policy and urban design, illustrating the impact of *Tempo 30* on travel times and offering an estimation of the effects of the RNMP on public transport operators and their future planning.

6. **Implementations for other cities:** The findings of this thesis are not only relevant to Zurich but also have the potential for application in other urban contexts with a similar road noise reduction strategy. As speed reductions are increasingly implemented in cities around the world, the methodologies and insights developed in this study offer valuable guidance. They provide a framework for estimating how changes in maximum speed limits may influence public transport networks in various cities, contributing to a broader understanding of the interplay between speed regulations, noise reduction, and transportation performance.

7. **Accessibility Analysis and Stop Configurations:** Through a scenario-based analysis using *Löwenbräu* and *Quellenstrasse* as a case study, this thesis demonstrates how stop configurations—removal or consolidation—affect walking accessibility for surrounding populations. These findings provide actionable insights for public transport operators to optimize stop placement and spacing.

## 7.2 Main Findings

The findings of this thesis highlight the varied impacts of Zurich's RNMP on public transport, particularly on buses and trams. The combined median additional travel times for both directions reached up to 32 minutes for the entire bus network, compared to significantly lower delays for the tram network, which reached up to 5 minutes. This discrepancy underscores the structural advantages of trams, such as UBK (independent rail bodies), which shield them from mixed-traffic conditions and enable more consistent travel times. Moreover, the analysis revealed almost no discernible differences in travel times between HVZ1 and HVZ2 for either transport mode, indicating a consistent impact of *Tempo 30* across both peak periods.

While the aggregated analysis provides valuable insights, it also demonstrates the importance of evaluating individual bus lines independently. For instance, Line 33 emerged as the most affected, with additional travel times of 4:59 minutes in HVZ1 and 4:51 minutes in HVZ2. Factors such as available turnaround times and interdependencies with other lines significantly influence how each route is impacted. Lines with limited operational buffers may require additional vehicles or timetable adjustments to maintain service reliability under the new speed limits.

The findings also highlight the role of stop spacing in travel time losses, with longer distances between stops amplifying the effects of *Tempo 30*. This analysis underscores the need for a tailored approach, evaluating the unique characteristics of each line to determine whether mitigation strategies, such as deploying additional vehicles or revising timetables, are necessary to minimize delays and maintain operational efficiency.

The accessibility analysis conducted in this thesis underscores the significant trade-offs involved in stop adjustments. The baseline scenario (Scenario 1), where both *Löwenbräu* and *Quellenstrasse* stops remain operational, provides the highest accessibility, with the largest number of building entrances reachable within the shortest walking distances. In contrast, scenarios involving stop removal or consolidation reduced accessibility, particularly in the 0–≤2 minute walking zone.

The Löwenbräu-only (Scenario 2) and Quellenstrasse-only (Scenario 3) scenarios showed notable decreases in accessibility, with fewer building entrances reachable within shorter walking distances compared to the baseline scenario (Scenario 1). However, the hypothetical stop scenario (Scenario 4), where both stops are replaced by a centrally located stop, provided a balanced but overall reduced accessibility. This highlights the trade-off between operational efficiency and equitable access for nearby residents.

These findings emphasize the importance of evaluating stop configurations on a case-by-case basis, as the impact of adjustments varies significantly depending on local context. Stop adjustments may provide an opportunity to partially mitigate the travel time increases caused by *Tempo 30*, particularly for lines or areas most affected by the new speed limits.

## 7.3 Limitations

Although this thesis provides information on the impacts of Zurich's RNMP, several limitations should be considered (cf. 6.4). The analysis relies on a two-month reference period, which, while stable, does not capture broader temporal variations such as seasonal changes, fluctuations in tourism, or commuting patterns. Furthermore, behavioral responses to *Tempo 30*, such as shifts in travel modes or changes in traffic volumes, were not accounted for, potentially influencing the results.

The use of 20-meter segments as the smallest unit of analysis, though detailed, introduces a certain degree of generalization, potentially smoothing out localized traffic dynamics. Additionally, the study assumes uniform compliance with the 30 km/h speed limit, excluding other factors such as traffic calming measures or changes to priority rules, which could further affect travel times.

For the accessibility analysis, simplified assumptions were made, including uniform walking speeds and a lack of consideration for socio-economic or demographic factors. These simplifications may not fully reflect real-world conditions or accessibility impacts for diverse population groups. Finally, the analysis does not evaluate the potential long-term effects of street infrastructure changes or variations in accessibility during peak and off-peak hours, which could influence the broader applicability of the findings.

## 7.4 Outlook

This thesis highlights the interplay between road noise mitigation measures, particularly the implementation of a 30 km/h speed limit, and their effects on public transport operations in the City of Zurich. While the focus of this study has been on travel times and accessibility, future research could explore additional co-benefits of speed reductions to provide a more comprehensive understanding of their impacts. These benefits include reducing the number and severity of accidents, lowering energy consumption, improving air quality, and enhancing urban livability (Yannis and Michelaraki, 2024). Furthermore, the implementation of 30 km/h in urban environments may encourage a modal shift towards walking and cycling, supporting sustainable urban mobility goals. Including these co-benefits in future analyses would offer a more holistic perspective on the outcomes of speed reductions in cities. The relationship between speed reductions and traffic flow also warrants further investigation. By smoothing traffic flow and reducing stop-and-go movements, the introduction of 30 km/h segments can promote a more predictable and harmonious coexistence among road users (Kanton Zurich, 2025). This may benefit both public transport and private vehicles, minimizing delays and improving efficiency in shared road spaces. Incorporating traffic flow into future research could provide a more realistic understanding of the broader impacts of speed reductions on urban mobility.

Since this thesis focuses solely on the effects of 30 km/h speed reductions as part of Zurich's RNMP, future studies could expand the scope to include additional measures such as low-noise paving and the promotion of electromobility. Incorporating these elements into the analysis could provide a more comprehensive understanding of the overall impact of the plan. For instance, analysing noise reduction values alongside financial implications for the city and public transport operators would offer valuable insights into the cost-effectiveness and feasibility of these measures. Such an approach would allow for a holistic evaluation of the plan, considering its environmental, operational, and economic effects.

The accessibility analysis in this thesis illustrates the trade-offs between stop removal or relocation and walking distances. Although adjusting stop configurations could mitigate some of the travel-time increases caused by *Tempo 30*, such changes must be evaluated on a case-by-case basis. Political opposition and logistical challenges often complicate the implementation of stop removals or relocations (Stadt Zurich Tiefbauamt, 2024), and the benefits of these measures depend heavily on the unique operational characteristics of each public transport line. Future studies should investigate these factors more deeply to ensure that public transport systems remain efficient, equitable and accessible while balancing the goals of urban mobility and noise mitigation. Finally, this thesis assumes a uniform walking speed for accessibility analysis. Future research could incorporate varying walking speeds to reflect differences among population groups, such as elderly residents or individuals with limited mobility. This would provide a more nuanced understanding of accessibility impacts and enhance the applicability of the findings for a representative urban environment.

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# Chapter A

# Overview Bus network Direction 2

## A.1 Comparison of Additional Median Time Need in the Bus Network during HVZ1 and HVZ2 (Direction 2)

Figure A.1 shows the bus network during HVZ1 (Direction 2), displayed using 20-meter segments. The map visualizes the median additional travel time experienced across the network, with different color gradations representing varying travel time increases. The lightest color corresponds to a range of 0.00–0.11 seconds, while the darkest color represents 0.75–1.08 seconds, indicating the areas where the largest increases in travel time occur.

Figure A.2 shows the bus network during HVZ2 (Direction 2) in 20-meter segments, with median additionaltime ranging from 0.00 to 0.93 seconds, highlighting areas with the greatest delays. The overall network has a sum of 2min and 14s.

Figures A.1 and A.2 show the additional median travel time for buses during HVZ1 and HVZ2 (Direction 2), respectively, in 20-meter segments. Both figures use a color gradient to represent varying additional travel times, with HVZ1 showing times ranging from 0.00 to 1.20 seconds and HVZ2 from 0.00 to 0.19 seconds. The areas with the largest delays compared to the reference period, are marked by darker colors, highlighting regions with significant travel time increases. Figures A.15 and A.16 provide the legends to interpret these color gradations. In general, HVZ1 shows a slightly broader range of additional time compared to HVZ2, indicating more significant delays in some areas during HVZ1.

**Overview of Additional Median Time Need in the Bus Network during HVZ1 (Direction 2)**

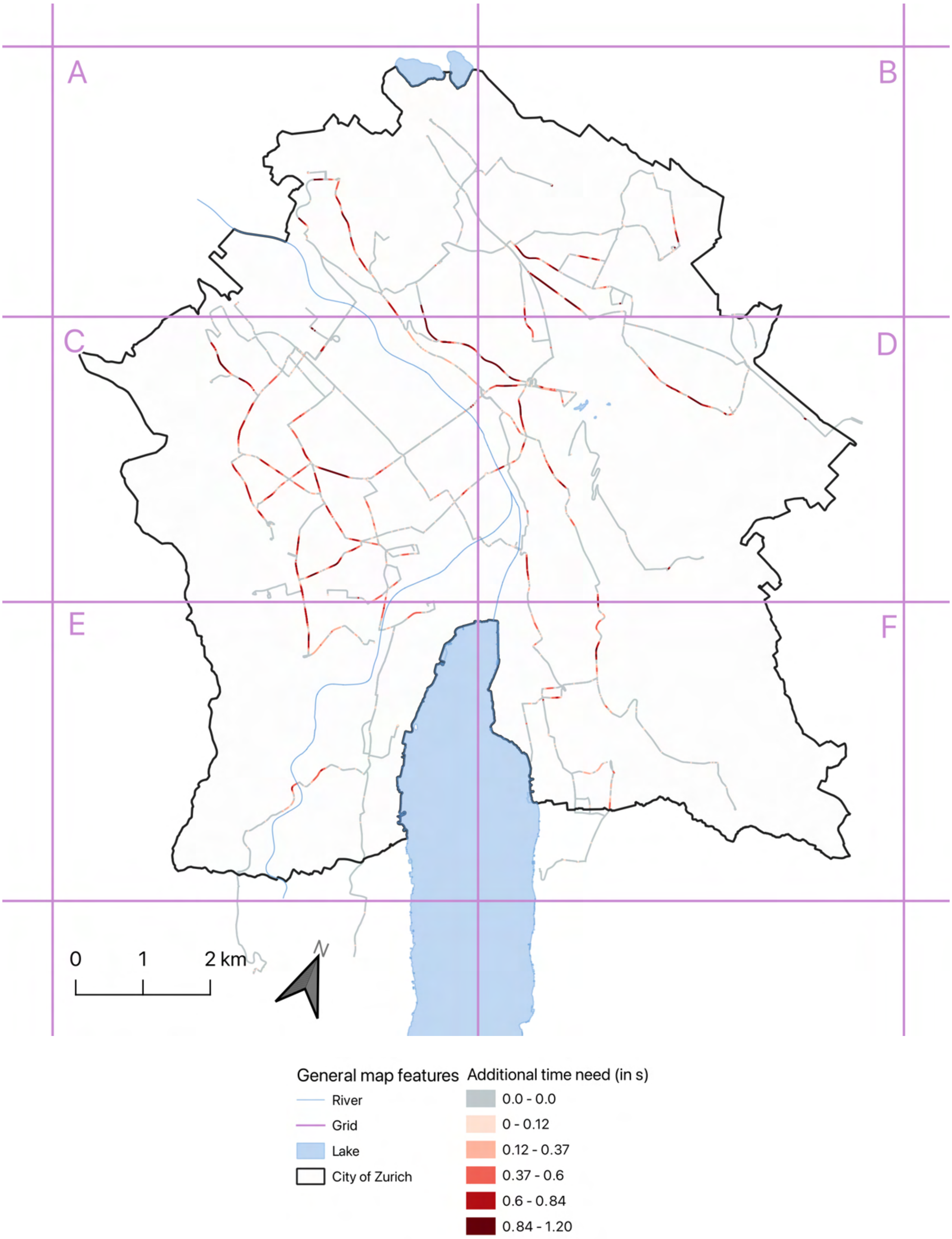


**Figure A.1:** Overview of the bus network during HVZ1 (Direction 2), displayed in 20-meter segments. The median additional time need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

**Overview of Additional Median Time Need in the Bus Network during HVZ2 (Direction 2)**

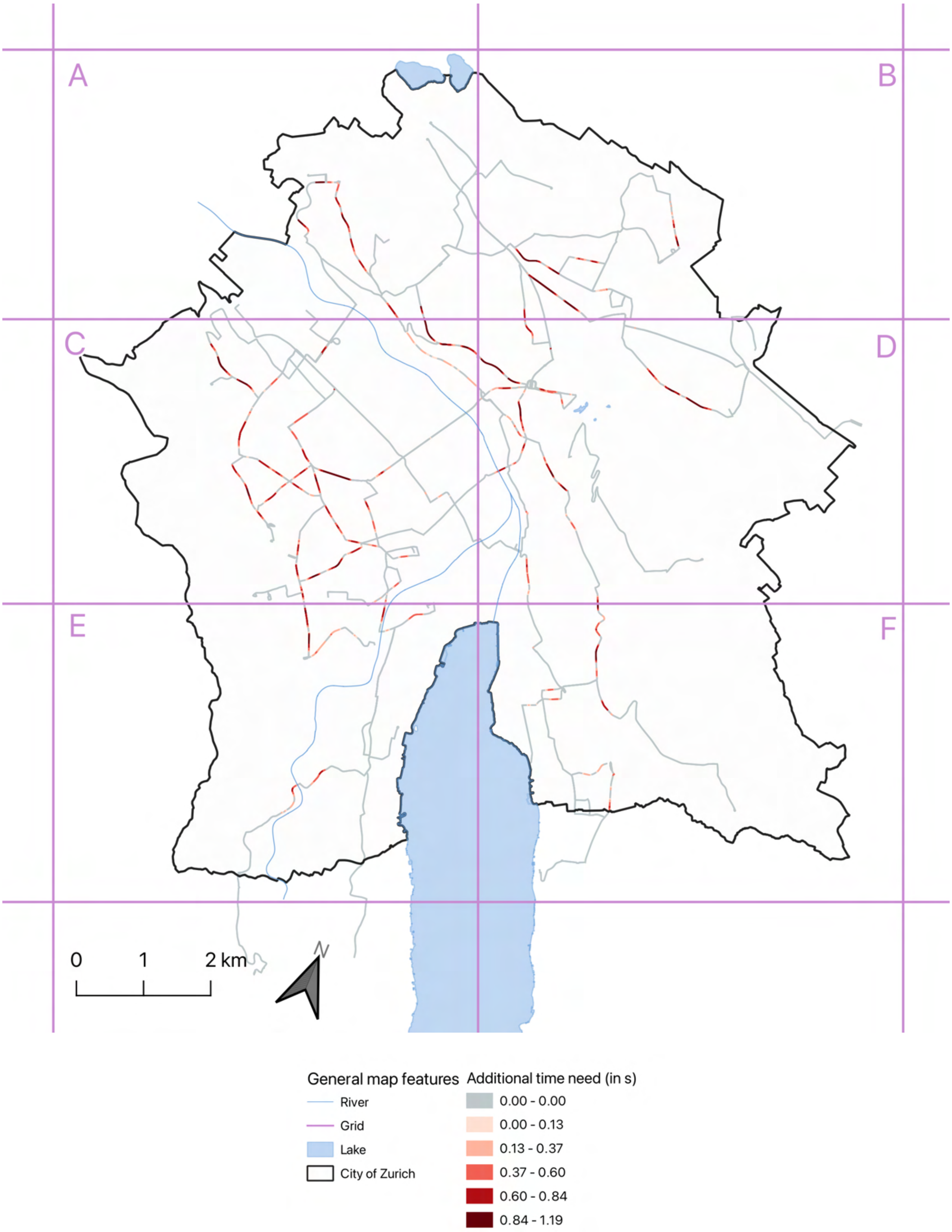


**Figure A.2:** Overview of the bus network during HVZ2 (Direction 2), displayed in 20-meter segments. The median additionaltime need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

### A.1.1 Close-up Views of the Bus Network (Direction 2)

#### Comparison of Additional Time Needed (in s) for Buses in Grid A during HVZ1 and HVZ2, Direction 2

Similar to direction 1 n both HVZ1 and HVZ2, several 20-meter segments show significant increases in additional travel time, particularly along the route between Schwert and Frankental. This section experiences a notable rise in travel time due to the implemented speed changes, as shown in Figures A.3 and A.4. The highest additional time is observed between Segantinistrasse and Giblenstrasse, reaching nearly 1.2 seconds per 20-meter segment.

#### Comparison of Additional Time Needed (in s) for Buses in Grid B during HVZ1 and HVZ2, Direction 1

When examining the additional travel time for buses in Grid B during HVZ1 (Figure 5.6) and HVZ2 (Figure 5.7), it is evident that the western part of the grid is most affected by the speed changes introduced by the RNMP. In both HVZ1 and HVZ2, the segments with the highest deviations from the reference period are located between Rautihalde and Rautistrasse, Felsenbergstrasse and Sackzelg, Albisrieden and Triemli, Hubertus and Altes Krematorium, and Friesenberg and Höfliweg, similar to direction 1. Additionally, in the northeastern part of the grid, the section between Im Wingert and Waidspital also shows higher values. These locations exhibit significant increases in travel time due to the speed restrictions, with values rising to around 1.18 seconds in HVZ1 and 1.19 seconds in HVZ2.

When comparing the two periods, HVZ1 and HVZ2, the overall patterns of additional travel time are very similar, with only slight differences, e.g. between Museum für Gestaltung and Bäckeranlage.

Compared to Grid A in direction 1 and 2, which has more concentrated segments with higher additional time values, Grid B shows a more dispersed distribution of segments with increased travel times, especially in the western regions. These findings suggest that while both HVZ1 and HVZ2 are affected by the new speed regulations, the differences between the two periods are relatively minor, and the additional time increases are mainly seen in the same sections across both HVZs.

#### Comparison of Additional Time Needed (in s) for Buses in Grid C during HVZ1 and HVZ2, Direction 2

In Grid C, during both HVZ1 and HVZ2, the highest differences in additional time compared to the reference period are observed, particularly in the northern part of the grid. The segments between Im Hagacker and Laubegg, Manesseplatz and Waffenplatzstrasse, as well as Verenastrasse and Bahnhof Leimbach, are most notably affected, as shown in Figures A.7 and A.8.

When comparing HVZ1 and HVZ2, only slight changes are visible.

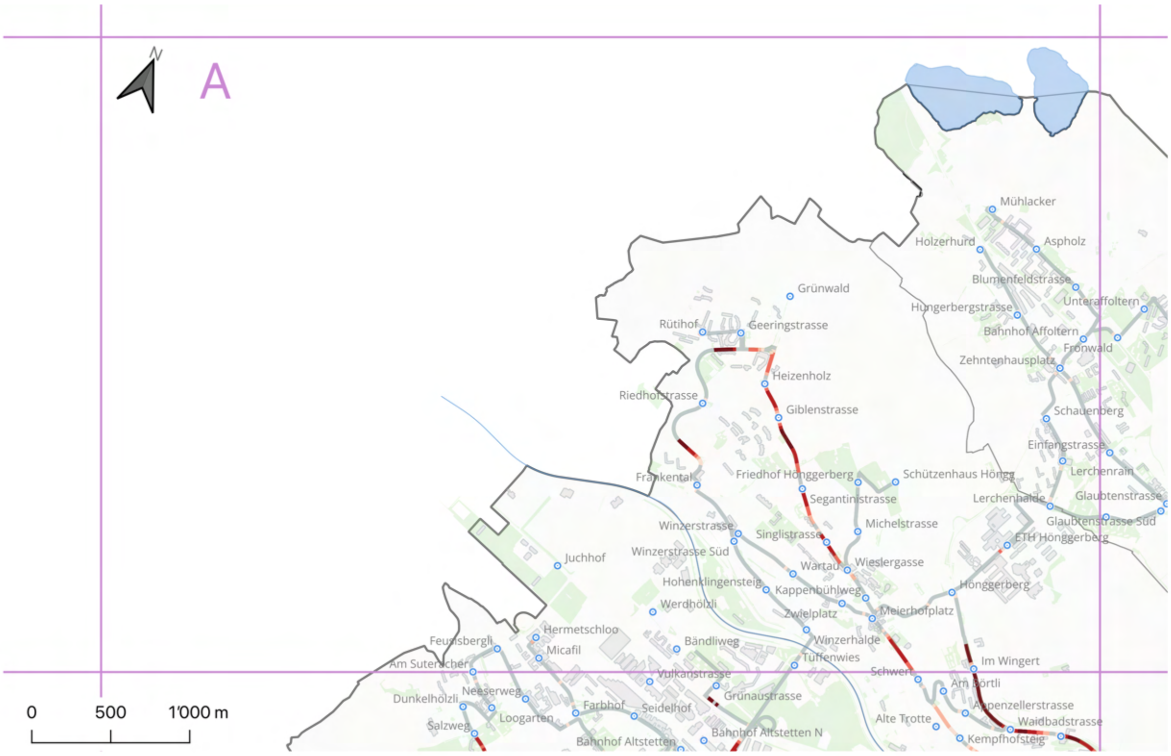


**Figure A.3:** Additional time need (in s) for buses in Grid A during HVZ1, Direction 2, in 20-meter segments. See Figure A.15 for detailed legend.

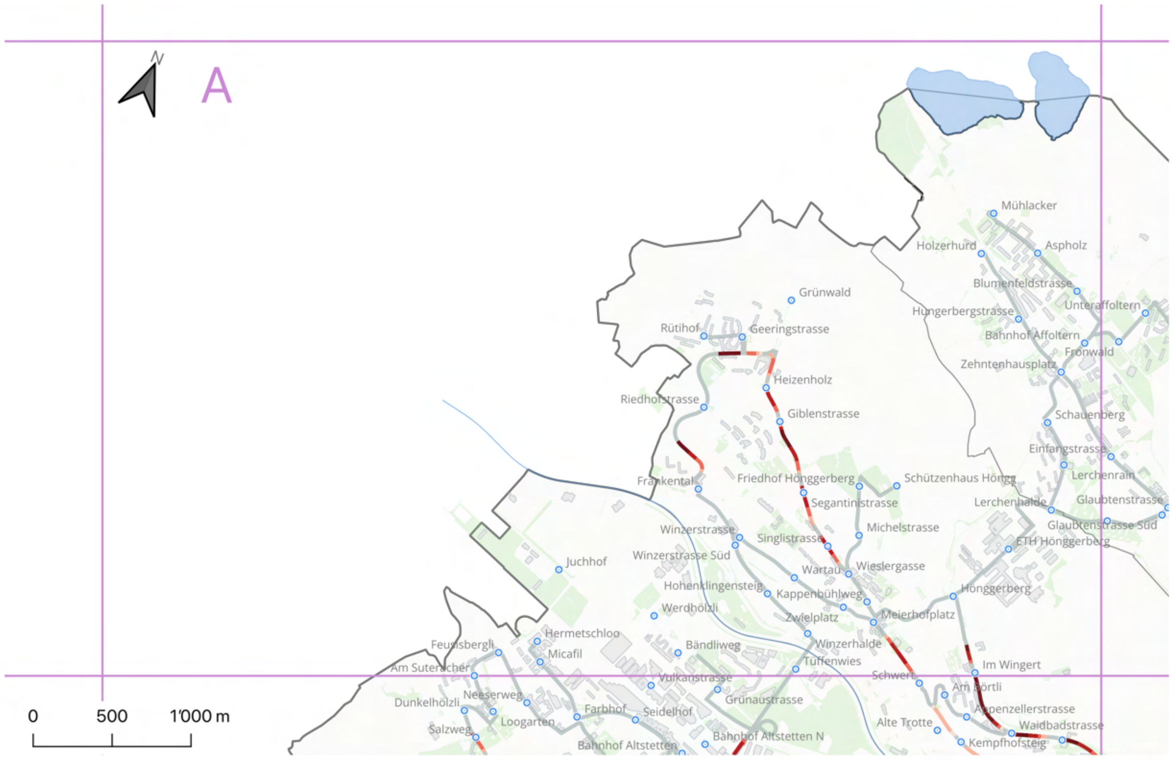


**Figure A.4:** Additional time need (in s) for buses in Grid A during HVZ2, Direction 2, in 20-meter segments. See Figure A.16 for detailed legend.


**Figure A.5:** Additional time need (in s) for buses in Grid B during HVZ1, Direction 2, in 20-meter segments. See Figure A.15 for detailed legend.


**Figure A.6:** Additional time need (in s) for buses in Grid B during HVZ2, Direction 2, in 20-meter segments. See Figure A.16 for detailed legend.

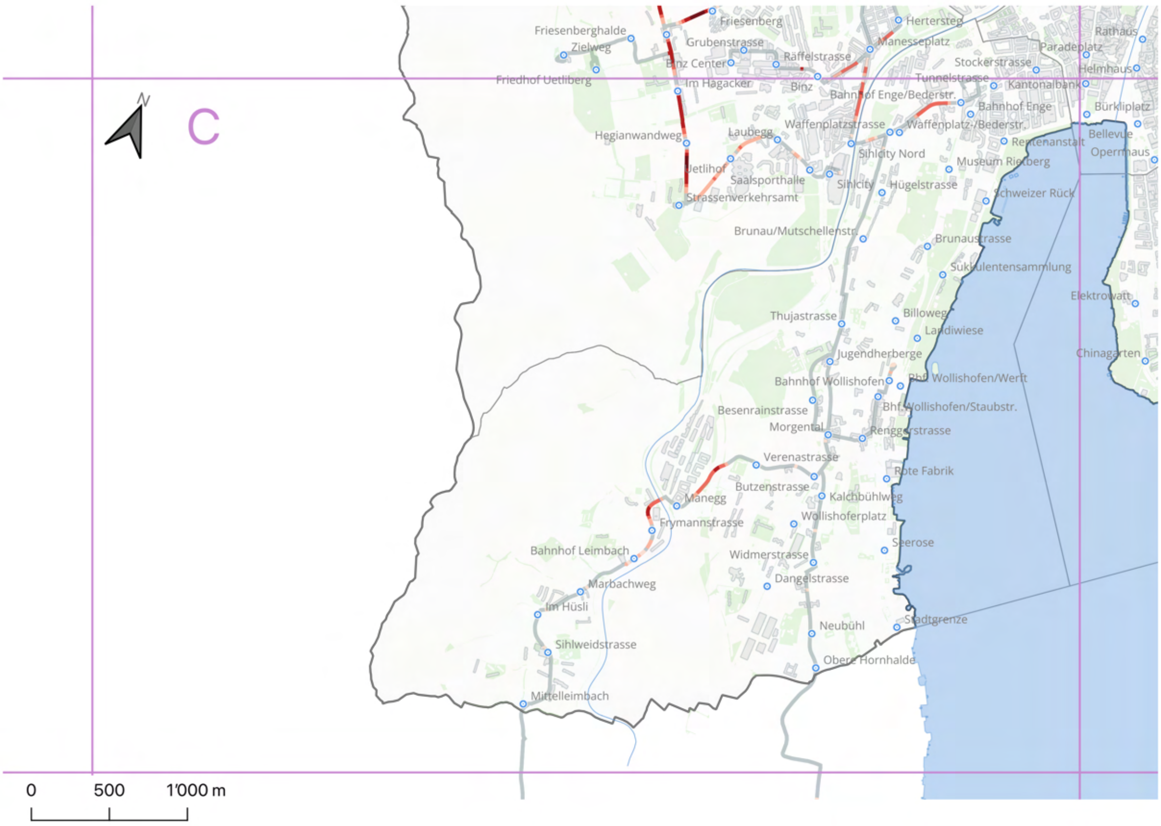


**Figure A.7:** Additional time need (in s) for buses in Grid C during HVZ1, Direction 2, in 20-meter segments. See Figure A.15 for detailed legend.

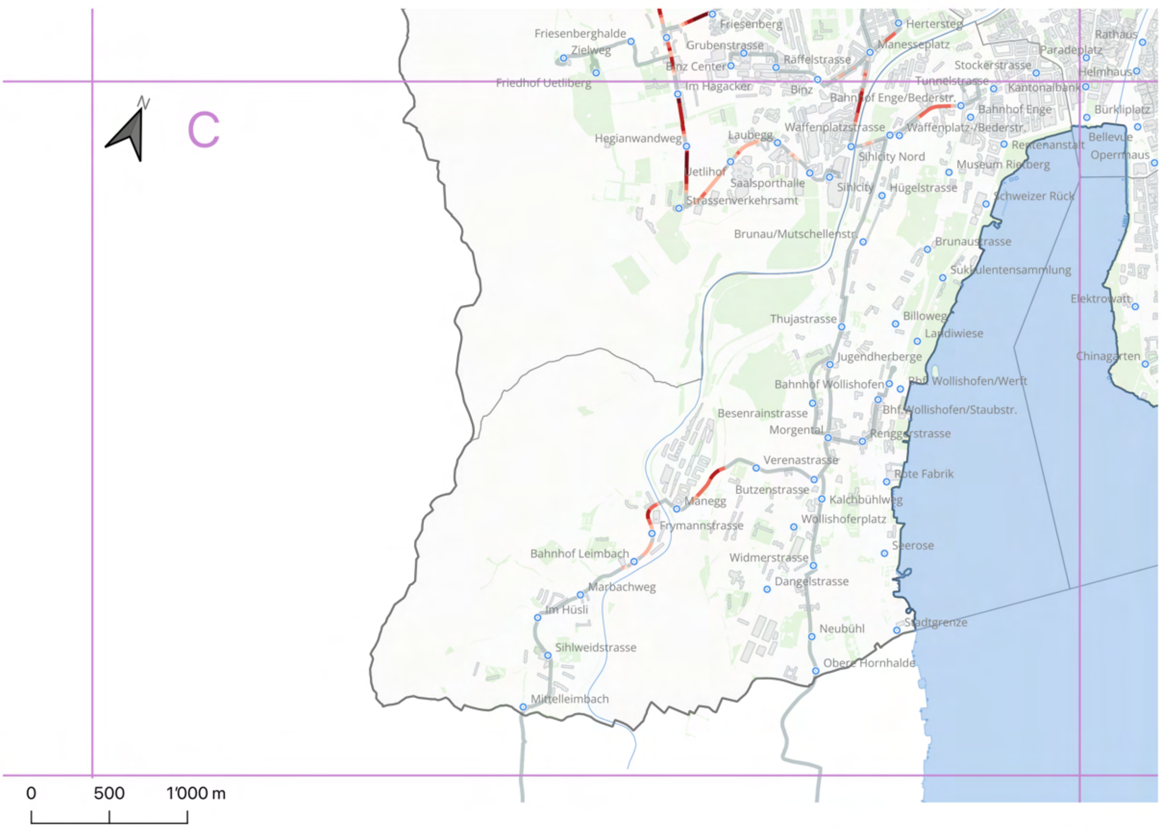


**Figure A.8:** Additional time need (in s) for buses in Grid C during HVZ2, Direction 2, in 20-meter segments. See Figure A.16 for detailed legend.

### Comparison of Additional Time Needed (in s) for Buses in Grid D during HVZ1 and HVZ2, Direction 2

In Grid D, the western and southwestern sections experience the most significant changes in additional time (0.87–1.19 s), particularly between Neuaffoltern and Bahnhof Oerlikon Nord, as shown in Figures A.9 and A.10. Additional time increases are also evident between Glaubtenstrasse Nord and Chaletweg, as well as small deviations between Maillartstrasse and Neunbrunnen. These changes in travel times align with the expected impact of speed regulation adjustments.

When comparing HVZ1 and HVZ2, only slight differences are observed, with the locations of the affected segments remaining consistent. The degree of additional time required, however, varies slightly between the two periods, with HVZ1 generally showing marginally higher values than HVZ2.

### Comparison of Additional Time Needed (in s) for Buses in Grid E during HVZ1 and HVZ2, Direction 1

In Grid E, during both HVZ1 and HVZ2, the highest values of additional time are observed in several long segments, particularly between Waidspital and Weihersteig, Lägernstrasse and Rotbuchstrasse, and Schaffhauserstrasse and Scheuchzerstrasse. Additionally, the segment between Frohburg and Friedrichstrasse is also notably affected by additional time, as shown in Figures 5.12 and 5.13.

In HVZ2 there is no additional time need between Dorfline and Friedackerstrasse, whereas in HVZ1 there is a small additional time need expected.

### Comparison of Additional Time Needed (in s) for Buses in Grid F during HVZ1 and HVZ2, Direction 1

In Grid F, the most significant difference between the reference period and the new speed regime is observed between Klosbach and Hönderlinsteg, as shown in Figures 5.14 and 5.15. Additionally, shorter segments between Botanischer Garten and Hegibachplatz, Hofstrasse and Klosbach and around Klinik Hirslanden, are also affected by the additional time need caused by the speed regulation changes. Similar to other grids, the comparison between HVZ1 and HVZ2 shows minor variations in the affected areas, with HVZ2 generally showing slightly higher values e.g. between Klusplatz and Kapfstrasse.

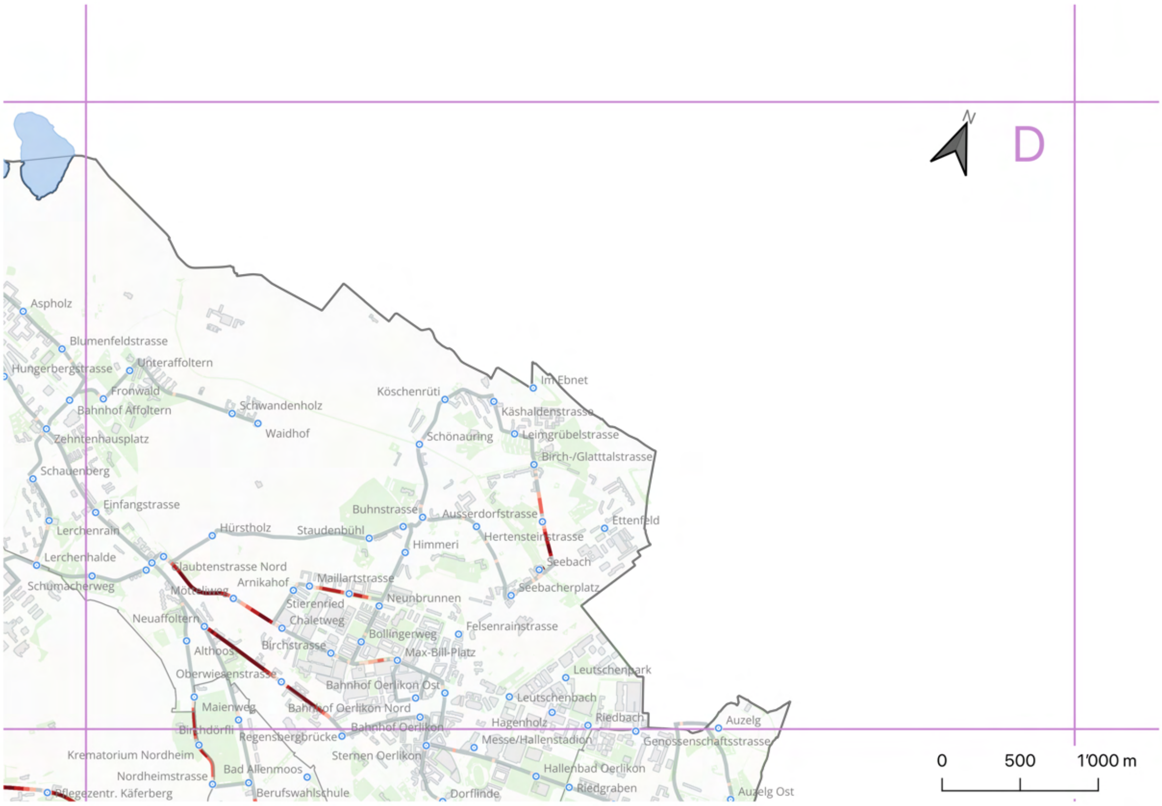


**Figure A.9:** Additional time need (in s) for buses in Grid D during HVZ1, Direction 2, in 20-meter segments. See Figure A.15 for detailed legend.

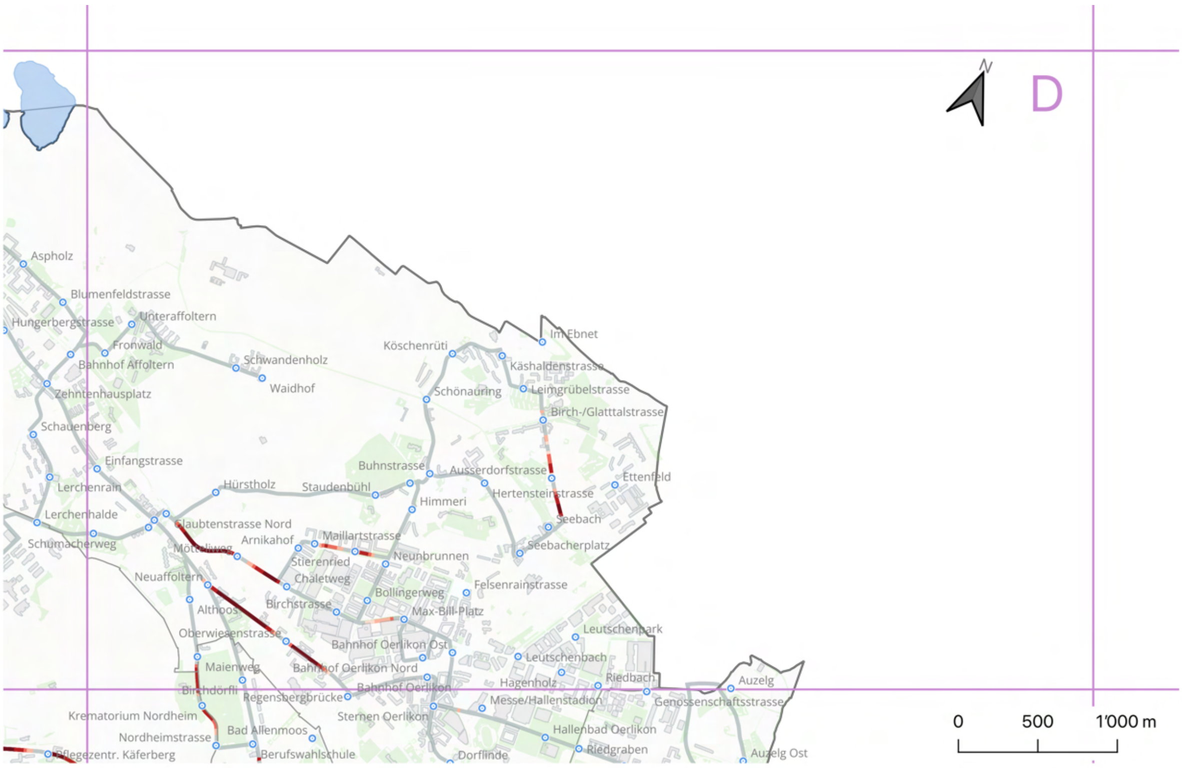


**Figure A.10:** Additional time need (in s) for buses in Grid D during HVZ2, Direction 2, in 20-meter segments. See Figure A.16 for detailed legend.

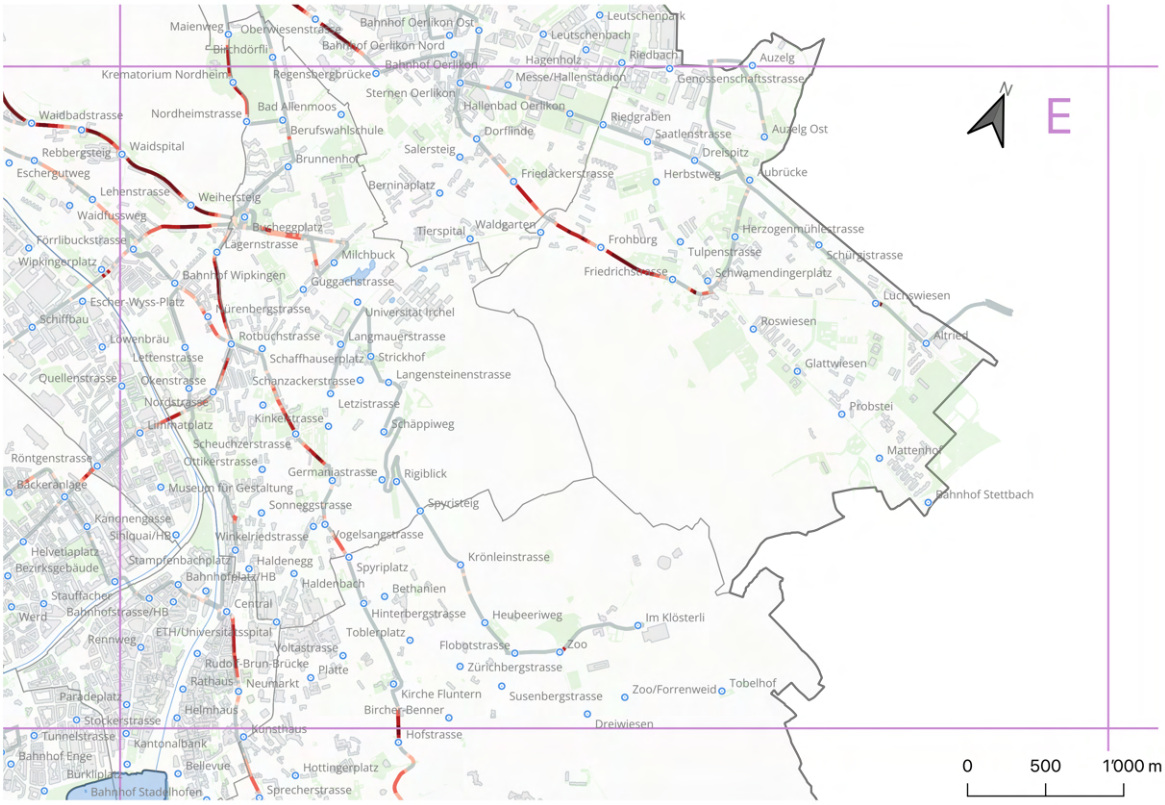


**Figure A.11:** Additional time need (in s) for buses in Grid E during HVZ1, Direction 2, in 20-meter segments. See Figure A.15 for detailed legend.


**Figure A.12:** Additional time need (in s) for buses in Grid E during HVZ2, Direction 2, in 20-meter segments. See Figure A.16 for detailed legend.

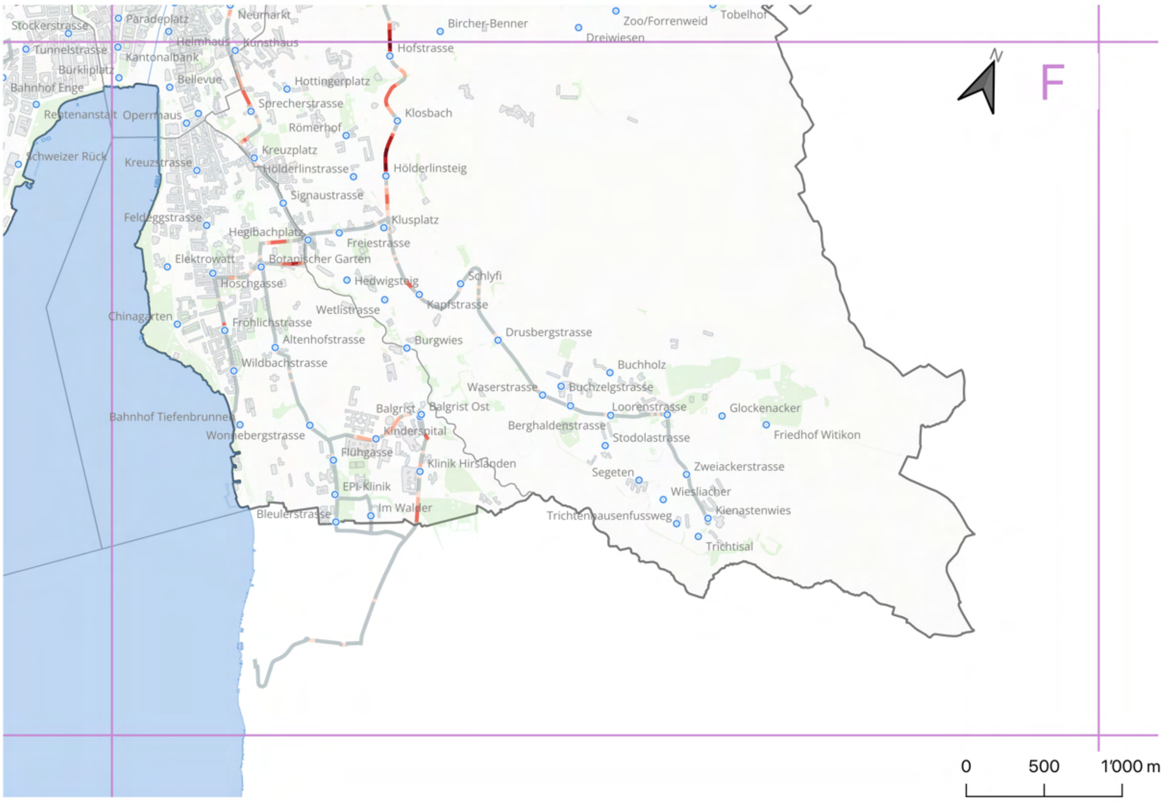


**Figure A.13:** Additional time need (in s) for buses in Grid F during HVZ1, Direction 2, in 20-meter segments. See Figure A.15 for detailed legend.

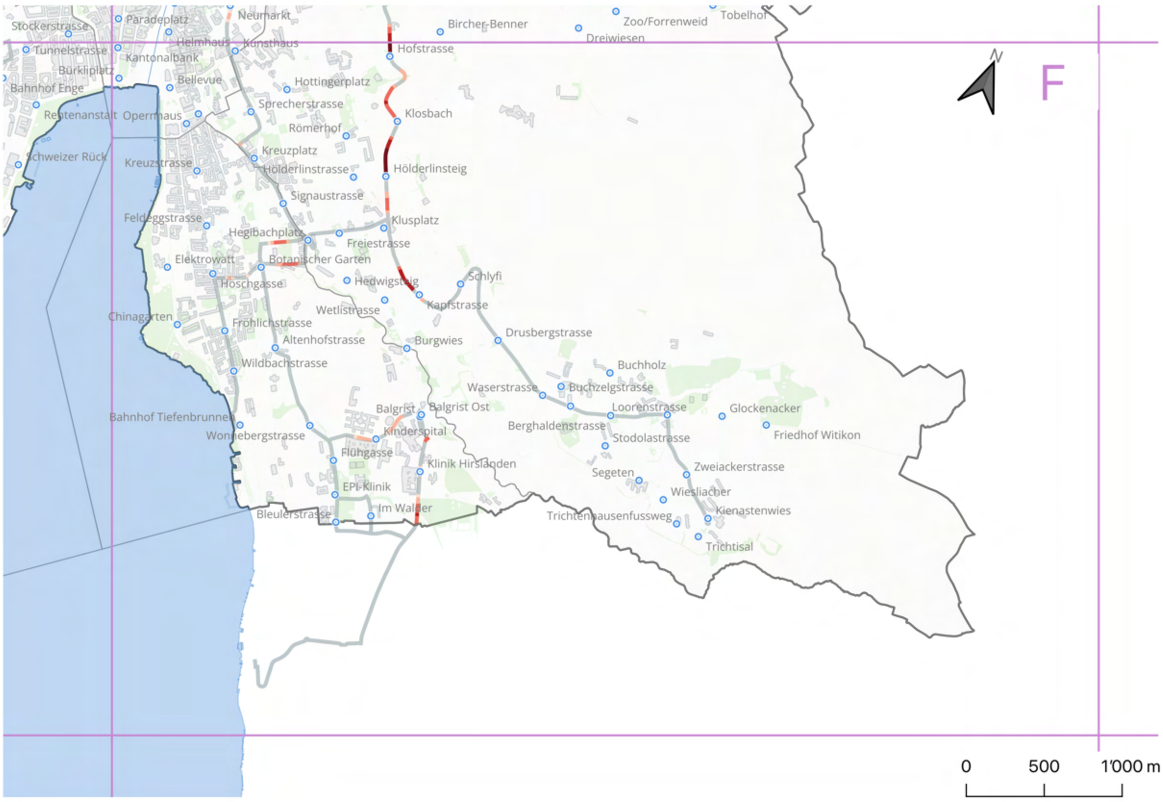


**Figure A.14:** Additional time need (in s) for buses in Grid F during HVZ2, Direction 2, in 20-meter segments. See Figure A.16 for detailed legend.

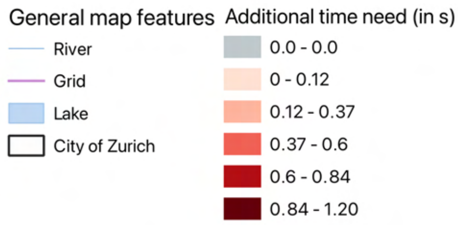


**Figure A.15:** Legend for buses in HVZ1 Direction 2 for grid A-F

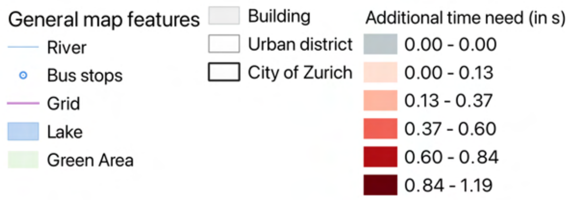


**Figure A.16:** Legend for buses in HVZ2 Direction 2 for grid A-F

# Chapter B

# Overview Tram Network Direction 1

## B.1 Comparison of Additional Median Time Need in the Tram Network during HVZ1 and HVZ2 (Direction 1)

Figure B.1 provides an overview of the tram network during HVZ1 (Direction 1), represented in 20-meter segments. The additional median time required per segment ranges from 0 to 0.903 seconds for HVZ1.

Similarly, Figure B.2 illustrates the tram network during HVZ2 (Direction 1) in 20-meter segments. During HVZ2, the additional median time required per segment ranges from 0.00 to 0.93 seconds, reflecting only a slightly higher maximum value compared to HVZ1. The total additional time for the entire network during HVZ2 amounts to 2 minutes and 14 seconds.

In terms of spatial distribution, the two HVZ periods exhibit comparable patterns, with similar hotspots observed across the network.

**Overview of Additional Median Time Need in the Tram Network during HVZ1 (Direction 1)**

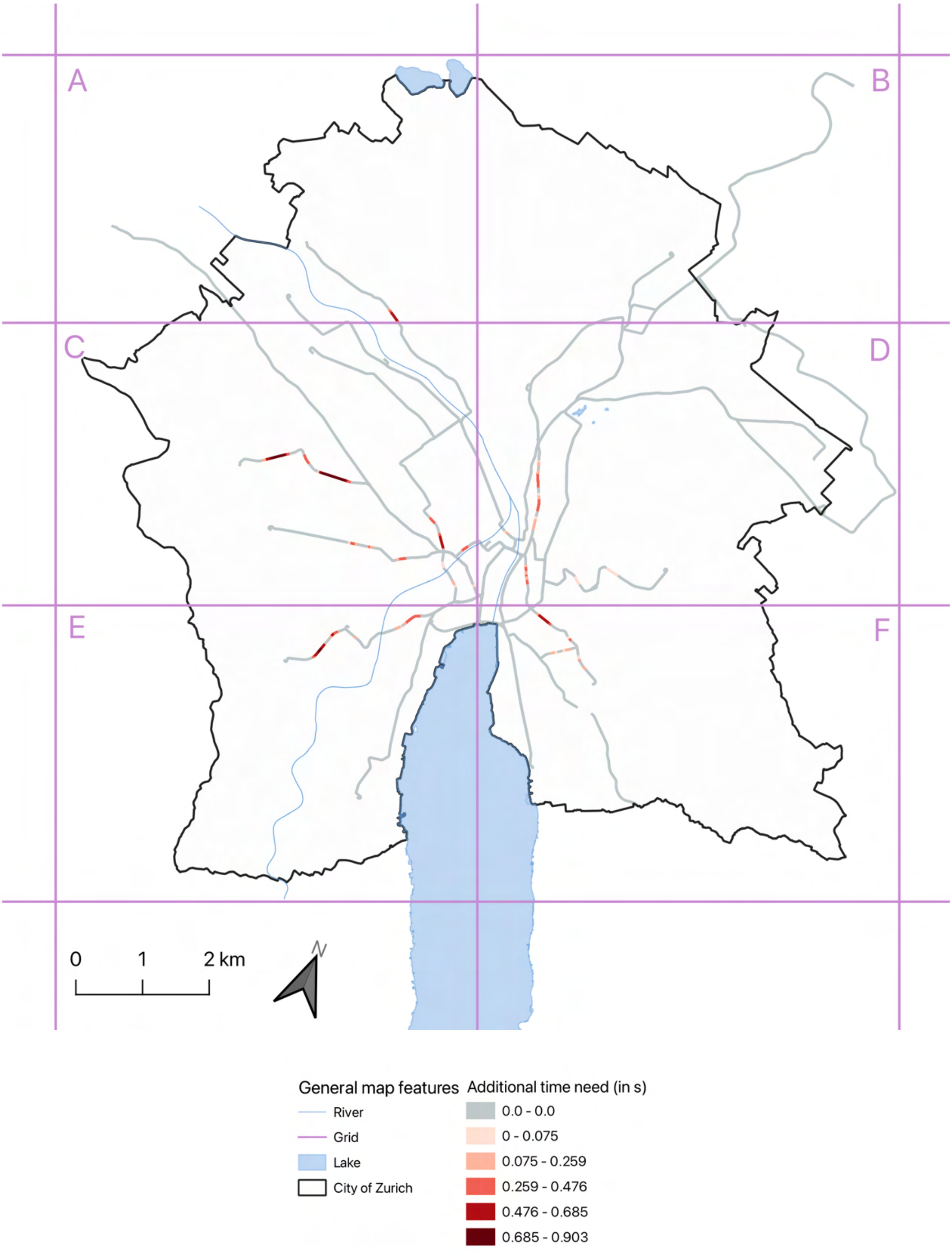


**Figure B.1:** Overview of the tram network during HVZ1 (Direction 1), displayed in 20-meter segments. The median additional time need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

**Overview of Additional Median Time Need in the Tram Network during HVZ2 (Direction 1)**

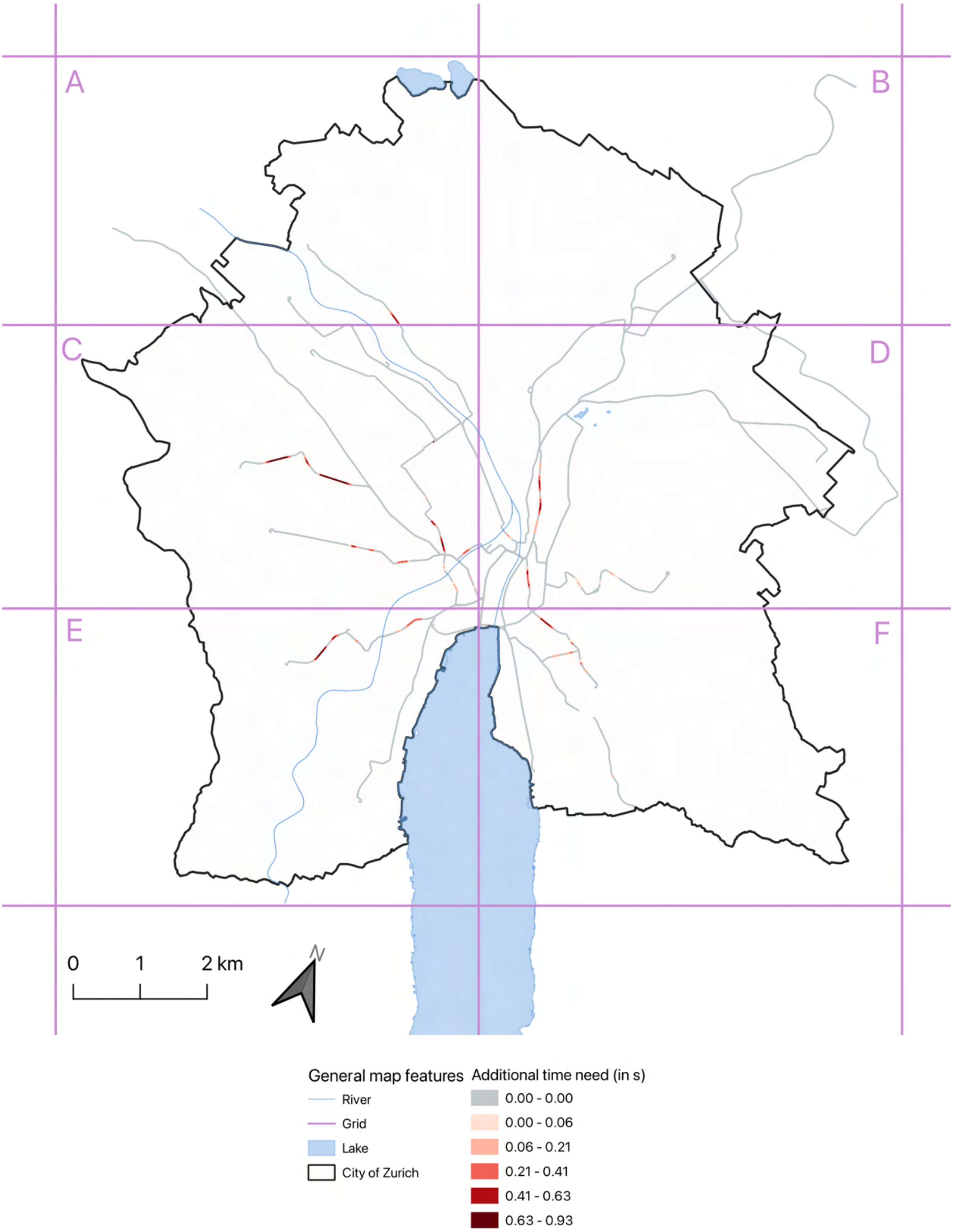


**Figure B.2:** Overview of the tram network during HVZ2 (Direction 1), displayed in 20-meter segments. The median additional time need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

### B.1.1 Close-up Views of the Tram Network (Direction 1)

#### Comparison of Additional Time Needed (in s) for Trams in Grid A during HVZ1 and HVZ2, Direction 1

Figures B.3 and B.4 illustrate the additional time required for trams in Grid A during HVZ1 and HVZ2, respectively, in 20-meter segments for Direction 1. The analysis reveals very similar results for the two primary traffic periods.

The only segment with noticeable additional time is located between Schwert and Meierhofplatz, as shown in both figures. In Figure B.3, which represents HVZ1, the segment displays a slightly elevated additional time need, aligning with the pattern observed during HVZ2 in Figure B.4. This consistency suggests that the additional time requirement in this specific area is independent of the traffic period.

Overall, the comparison indicates minimal variations in additional time requirements across the grid during the two traffic periods.

#### Comparison of Additional Time Needed (in s) for Buses in Grid B during HVZ1 and HVZ2, Direction 1

Figures B.5 and B.6 illustrate the additional time needed for buses in Grid B during HVZ1 and HVZ2, respectively, in 20-meter segments for Direction 1. The results for HVZ1 and HVZ2 are largely similar, with notable segments showing additional time requirements in both periods.

The longest segments with additional time are located between the stops Siemens and Fellenbergstrasse, as well as between Hubertus and Altes Krematorium. These segments are consistently highlighted in both traffic periods.

When comparing the additional time between HVZ1 and HVZ2 for the segment between Siemens and Hubertus, a slight difference is observed. During HVZ2, the segment falls into the highest class of additional time need (0.63–0.93 seconds), whereas no 20-meter segments in HVZ1 belong to this highest class. This indicates a higher delay during HVZ2 for this specific segment.

Additionally, a small deviation is observed for the segment between Güterbahnhof and Bäckeranlage. During HVZ2, a minor increase in additional time is evident compared to the reference period. In contrast, no differences are detected for this segment during HVZ1.

Overall, while the patterns in additional time requirements for buses in Grid B are largely consistent across HVZ1 and HVZ2, these differences highlight specific localized deviations in delay during HVZ2.

#### Comparison of Additional Time Needed (in s) for Trams in Grid C during HVZ1 and HVZ2, Direction 1

Figures B.7 and B.8 depict the additional travel time for trams in Grid C during HVZ1 and HVZ2 in Direction 1. The analysis reveals a high degree of similarity between the two primary traffic periods.

Significant hotspots with elevated additional travel time are observed between Strassenverkehrsamt and Uetlihof, as well as between Uetlihof and Laubegg. These segments exhibit slightly higher additional travel time during HVZ2 compared to HVZ1. Another notable hotspot is located between Waffenplatzstrasse and Bahnhof Enge/Bederstrasse, which demonstrates consistently elevated additional travel time in both HVZ1 and HVZ2.

Overall, the comparison highlights minimal differences in additional travel time across the grid between the two traffic periods.

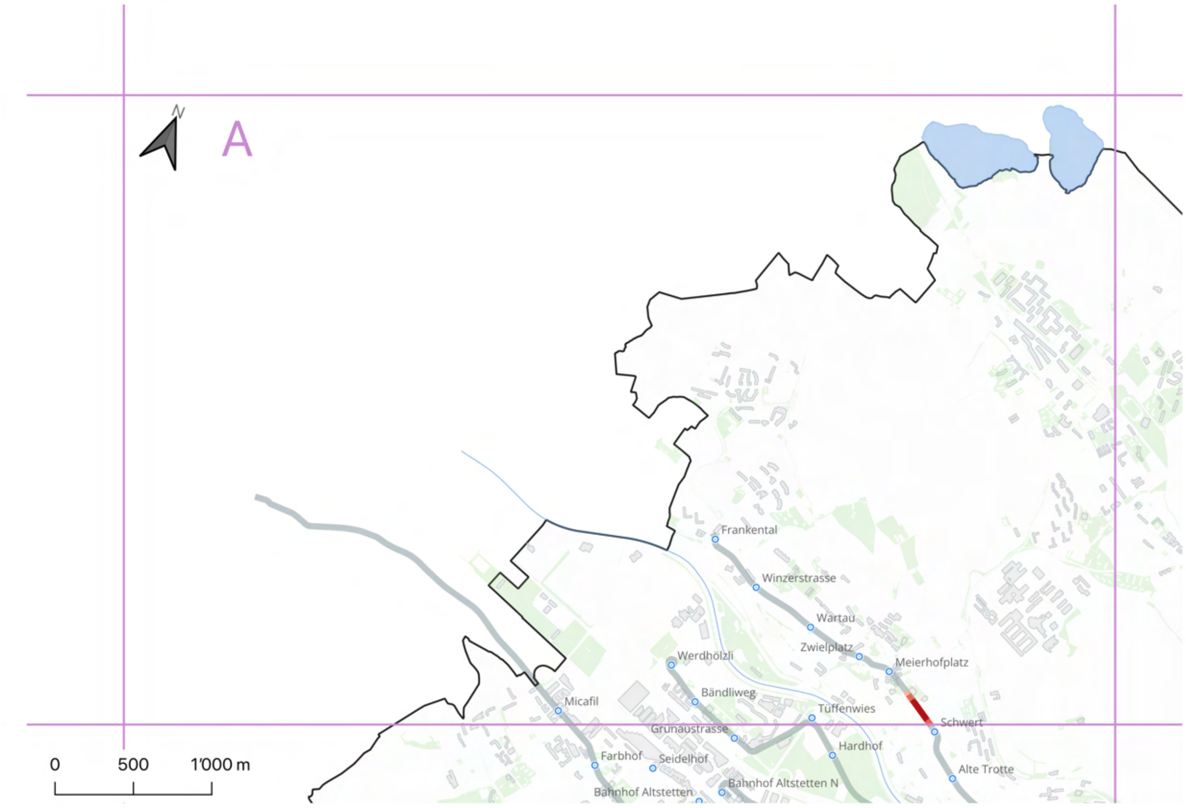


**Figure B.3:** Additional time need (in s) for trams in Grid A during HVZ1, Direction 1, in 20-meter segments. See Figure B.15 for detailed legend.

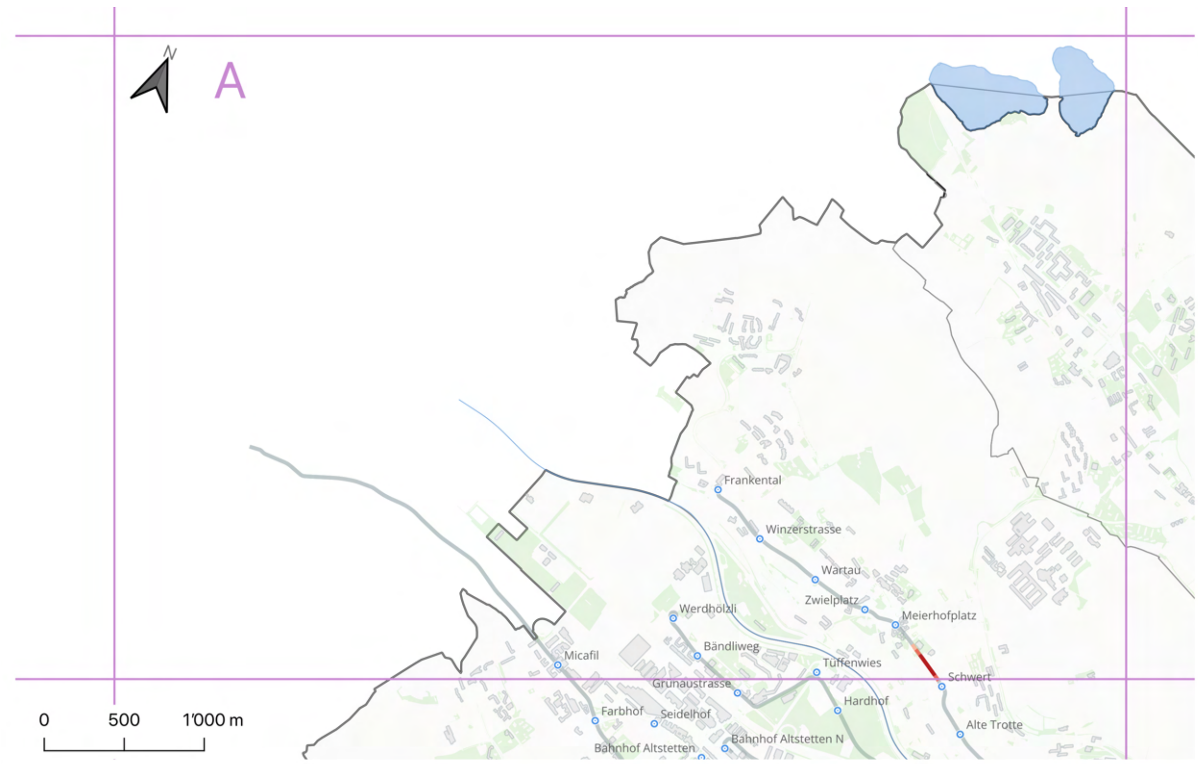


**Figure B.4:** Additional time need (in s) for trams in Grid A during HVZ2, Direction 1, in 20-meter segments. See Figure B.16 for detailed legend.


**Figure B.5:** Additional time need (in s) for trams in Grid B during HVZ1, Direction 1, in 20-meter segments. See Figure B.15 for detailed legend.


**Figure B.6:** Additional time need (in s) for trams in Grid B during HVZ2, Direction 1, in 20-meter segments. See Figure B.16 for detailed legend.

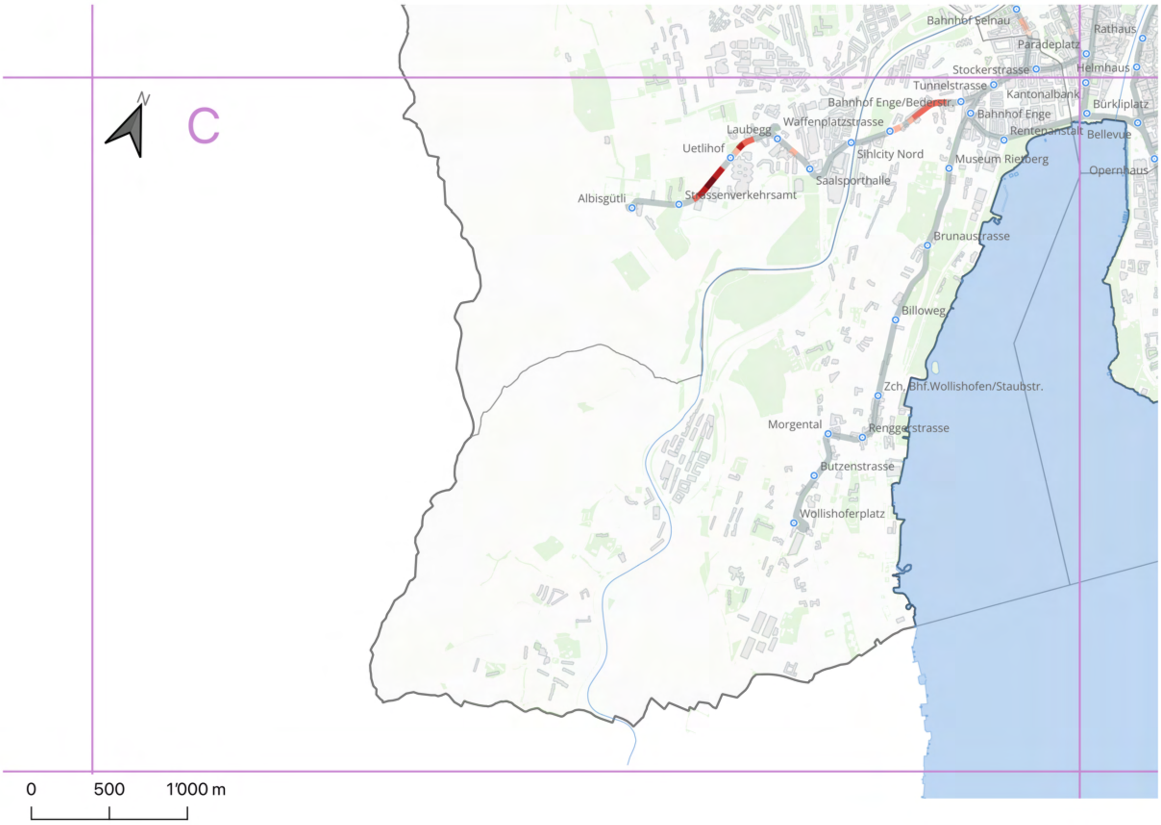


**Figure B.7:** Additional time need (in s) for trams in Grid C during HVZ1, Direction 1, in 20-meter segments. See Figure B.15 for detailed legend.

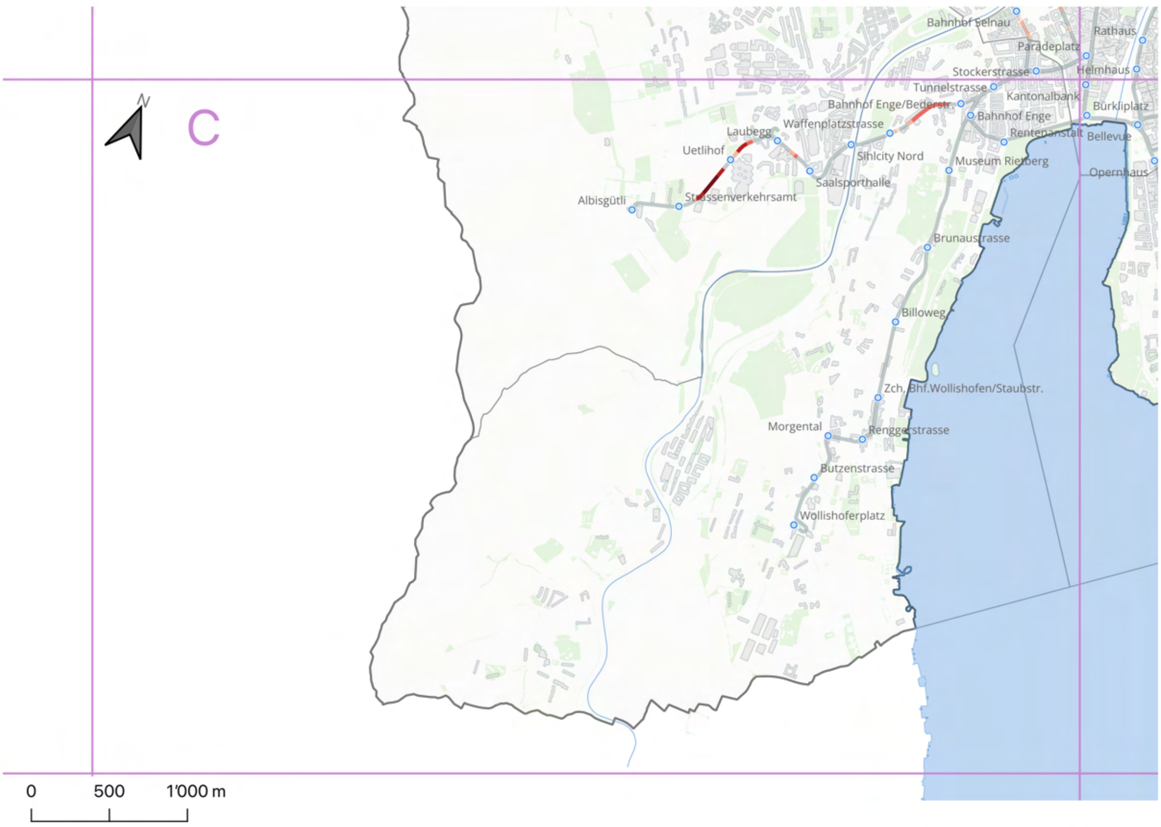


**Figure B.8:** Additional time need (in s) for trams in Grid C during HVZ2, Direction 1, in 20-meter segments. See Figure B.16 for detailed legend.

### Comparison of Additional Time Needed (in s) for Buses in Grid D during HVZ1 and HVZ2, Direction 1

The analysis of Grid D during HVZ1 and HVZ2, as shown in Figures 5.10 and 5.11, indicates no significant additional travel time for buses in Direction 1 across both traffic periods.

This finding suggests that bus operations in Grid D remain largely unaffected during both HVZ1 and HVZ2.

### Comparison of Additional Time Needed (in s) for Trams in Grid E during HVZ1 and HVZ2, Direction 1

Figures B.11 and B.12 illustrate the additional travel time for trams in Grid E during HVZ1 and HVZ2 in Direction 1. The results indicate a high degree of similarity between the two primary traffic periods.

The most affected segments include those between Röslistrasse and Ottikerstrasse, Ottikerstrasse and Soneggstrasse, as well as between Bahnhofplatz/HB and Neumarkt. These areas consistently show elevated additional travel times.

### Comparison of Additional Time Needed (in s) for Buses in Grid F during HVZ1 and HVZ2, Direction 1

Figures B.13 and B.14 present the additional travel time for buses in Grid F during HVZ1 and HVZ2 in Direction 1. The results are largely similar across the two traffic periods, with some notable differences.

The highest discrepancies in travel time for HVZ1 and HVZ2 between the reference period and the speed adjustments due to the RNMP are observed between Kunsthaus and Hottingerplatz. Additionally, slightly higher values are noted for HVZ2 on the segment between Römerhof and Englischviertelstrasse, suggesting increased delays during the afternoon traffic period.

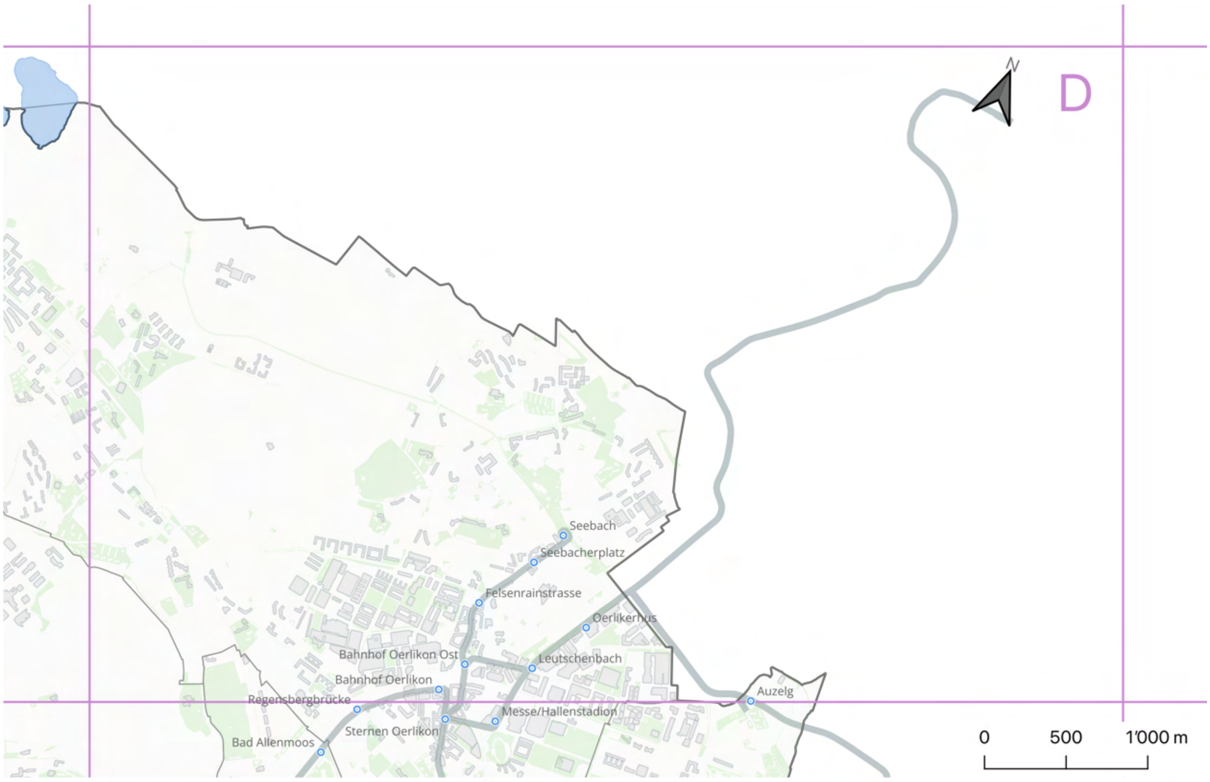


**Figure B.9:** Additional time need (in s) for trams in Grid D during HVZ1, Direction 1, in 20-meter segments. See Figure B.15 for detailed legend.

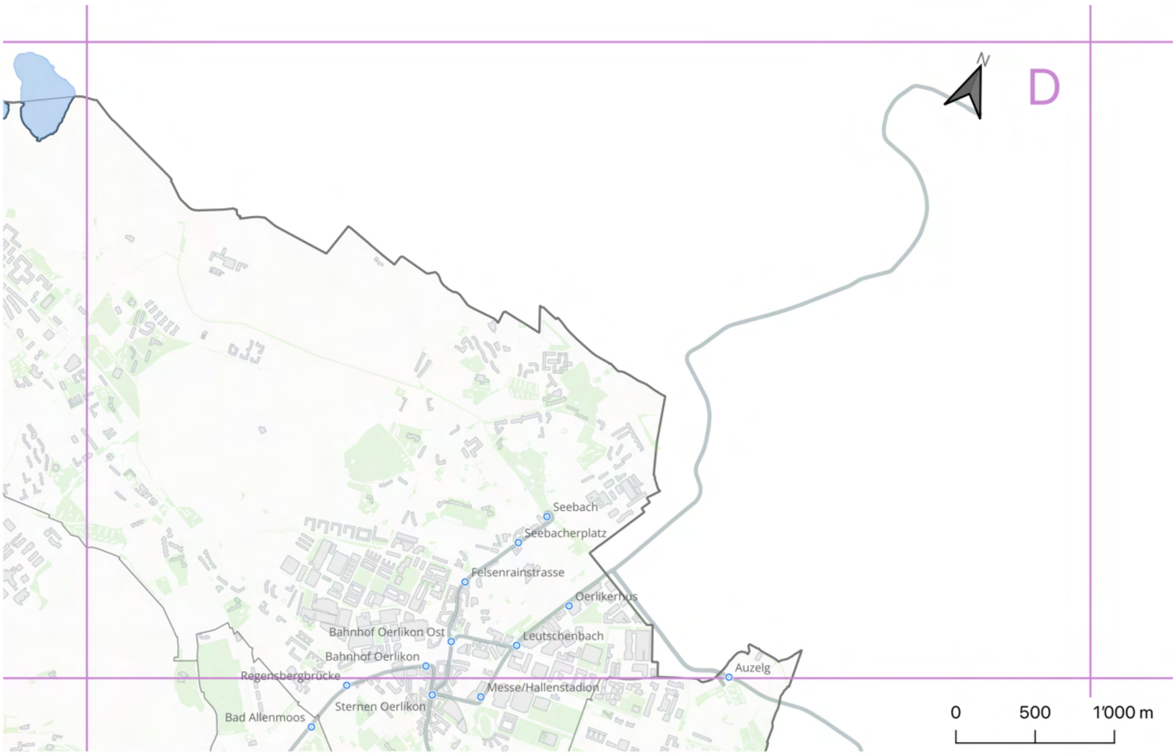


**Figure B.10:** Additional time need (in s) for trams in Grid D during HVZ2, Direction 1, in 20-meter segments. See Figure B.16 for detailed legend.

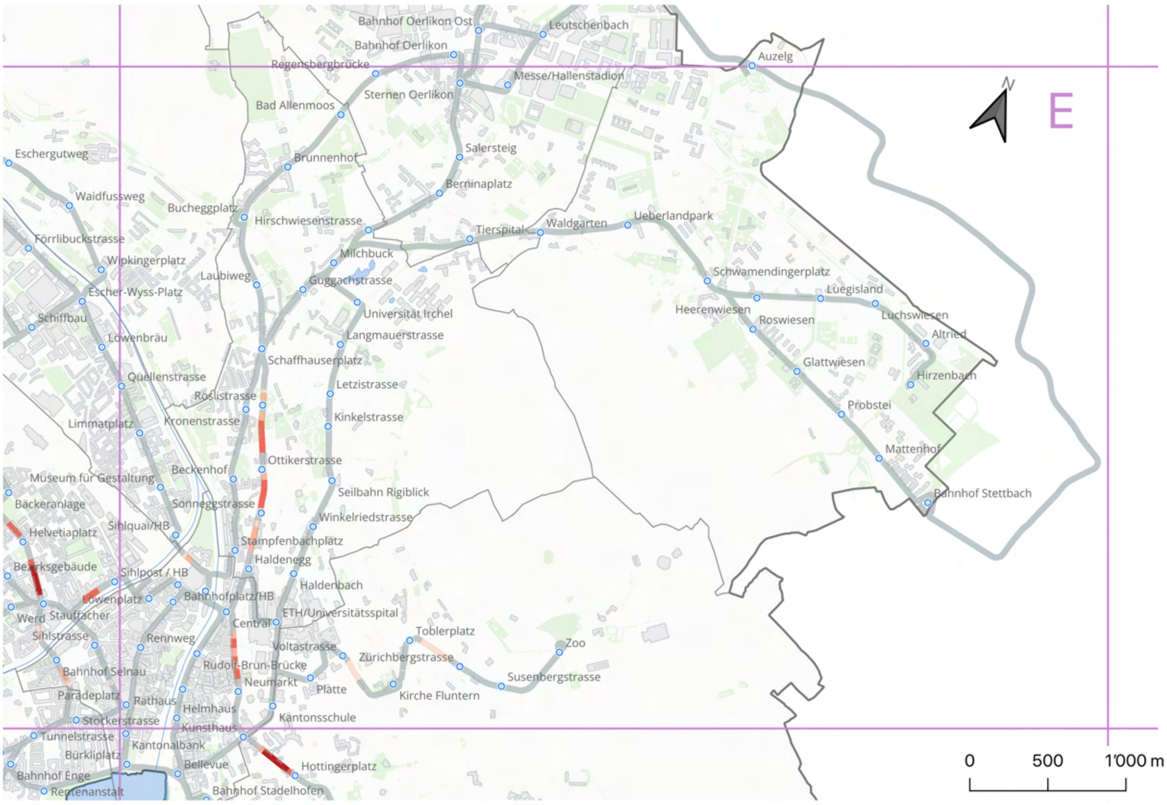


**Figure B.11:** Additional time need (in s) for trams in Grid E during HVZ1, Direction 1, in 20-meter segments. See Figure B.15 for detailed legend.

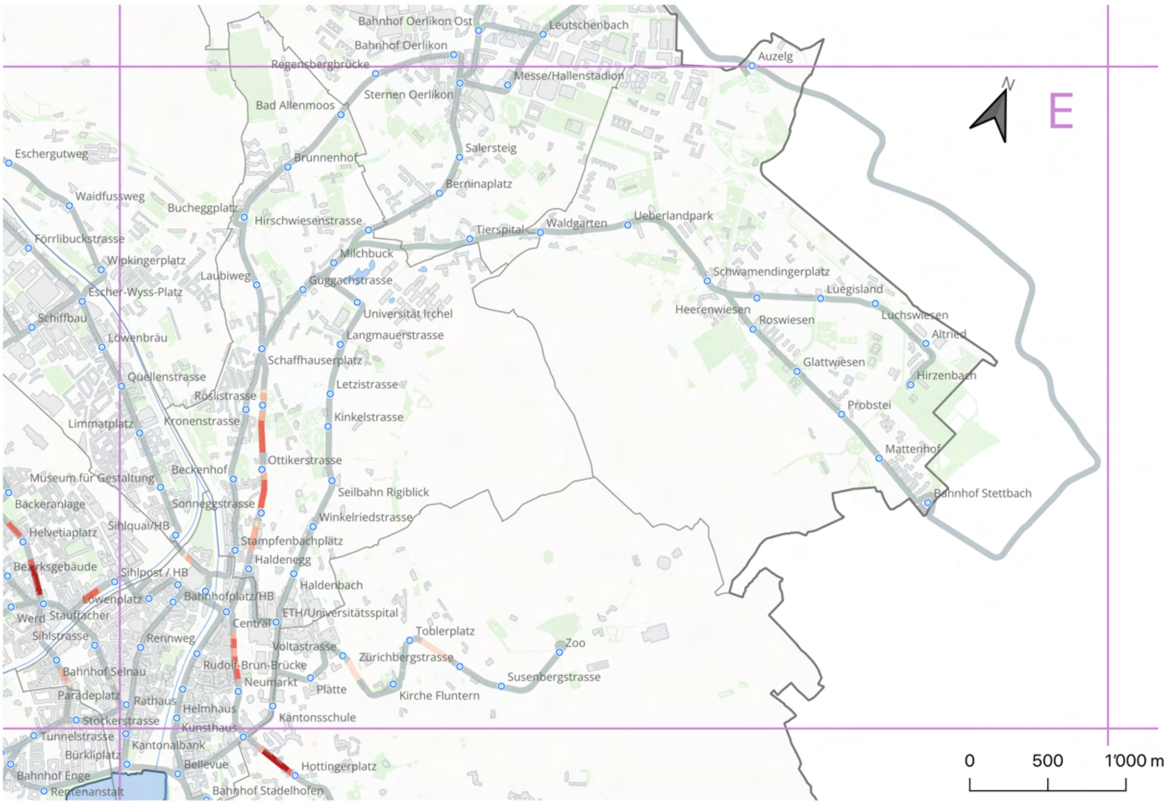


**Figure B.12:** Additional time need (in s) for trams in Grid E during HVZ2, Direction 1, in 20-meter segments. See Figure B.16 for detailed legend.


**Figure B.13:** Additional time need (in s) for trams in Grid F during HVZ1, Direction 1, in 20-meter segments. See Figure B.15 for detailed legend.


**Figure B.14:** Additional time need (in s) for trams in Grid F during HVZ2, Direction 1, in 20-meter segments. See Figure B.16 for detailed legend.

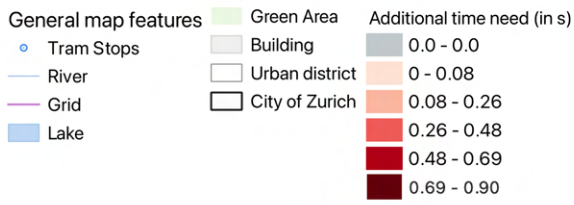


**Figure B.15:** Legend for tram in HVZ1 Direction 1 for grid A-F

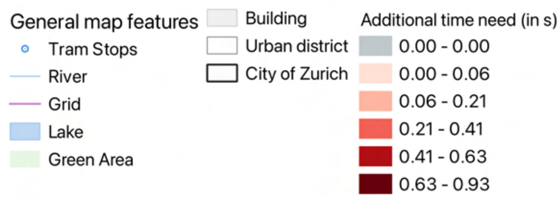


**Figure B.16:** Legend for tram in HVZ2 Direction 1 for grid A-F

# Chapter C

# Overview Tram Network Direction 2

## C.1 Comparison of Additional Median Time Need in the Tram Network during HVZ1 and HVZ2 (Direction 2)

Figure C.1 presents the tram network during HVZ1 (Direction 1), displayed in 20-meter segments. The map visualizes the median additional travel time across the network, with a color gradient indicating variations in delays. The observed additional travel time ranges from 0 to 0.90 seconds per segment, highlighting areas with minor to moderate delays.

Similarly, Figure C.2 illustrates the tram network during HVZ2 (Direction 1), also in 20-meter segments. The median additional travel time in this period ranges from 0.00 to 0.93 seconds, with the map emphasizing the segments experiencing the highest delays.

Overall, the results indicate a consistent pattern of median additional travel time across the tram network during HVZ1 and HVZ2, with slightly higher values observed in HVZ2. These findings suggest minor temporal variations in delay magnitudes between the two traffic periods.

**Overview of Additional Median Time Need in the Tram Network during HVZ1 (Direction 2)**

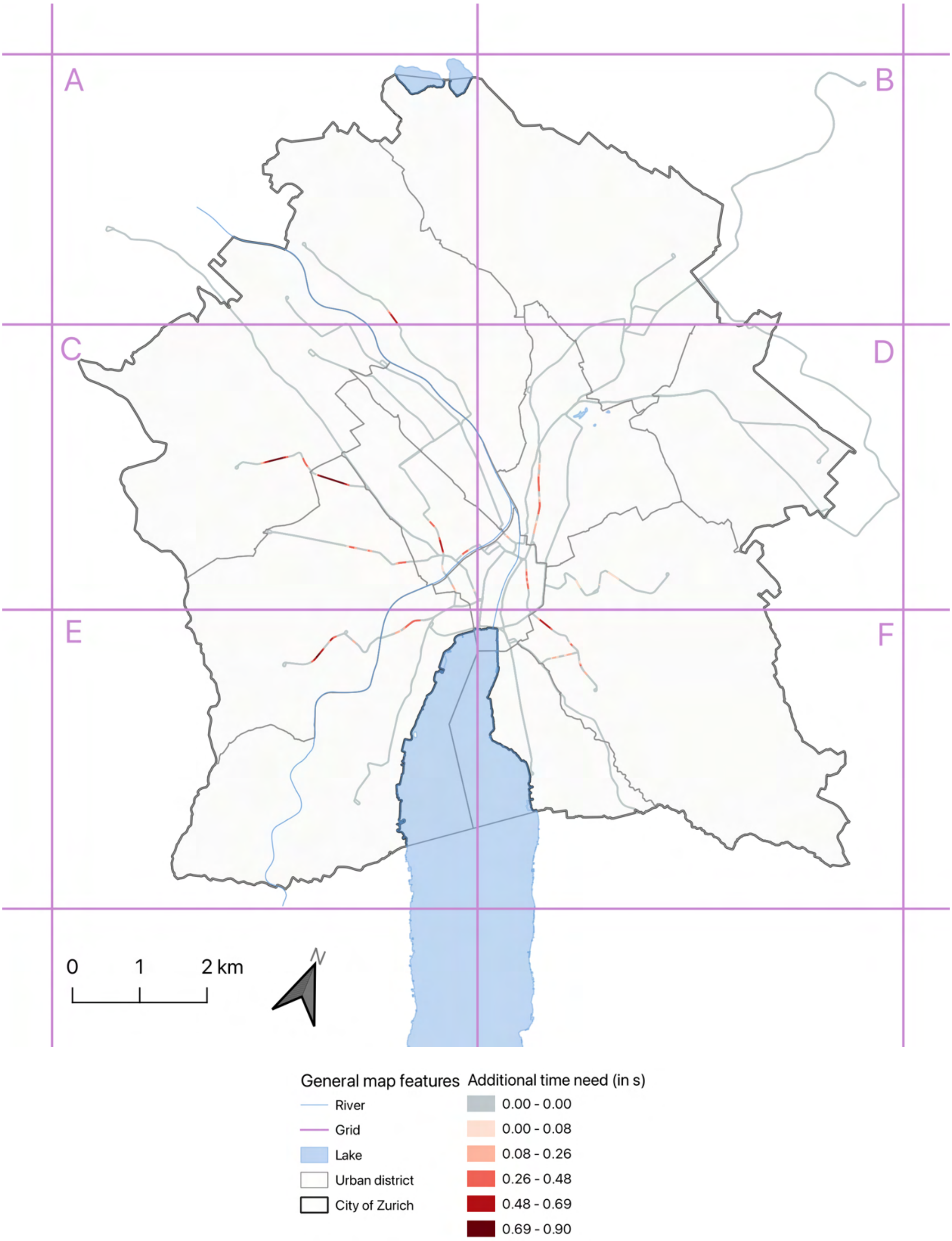


**Figure C.1:** Overview of the tram network during HVZ1 (Direction 2), displayed in 20-meter segments. The median additional time need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

**Overview of Additional Median Time Need in the Tram Network during HVZ2 (Direction 2)**

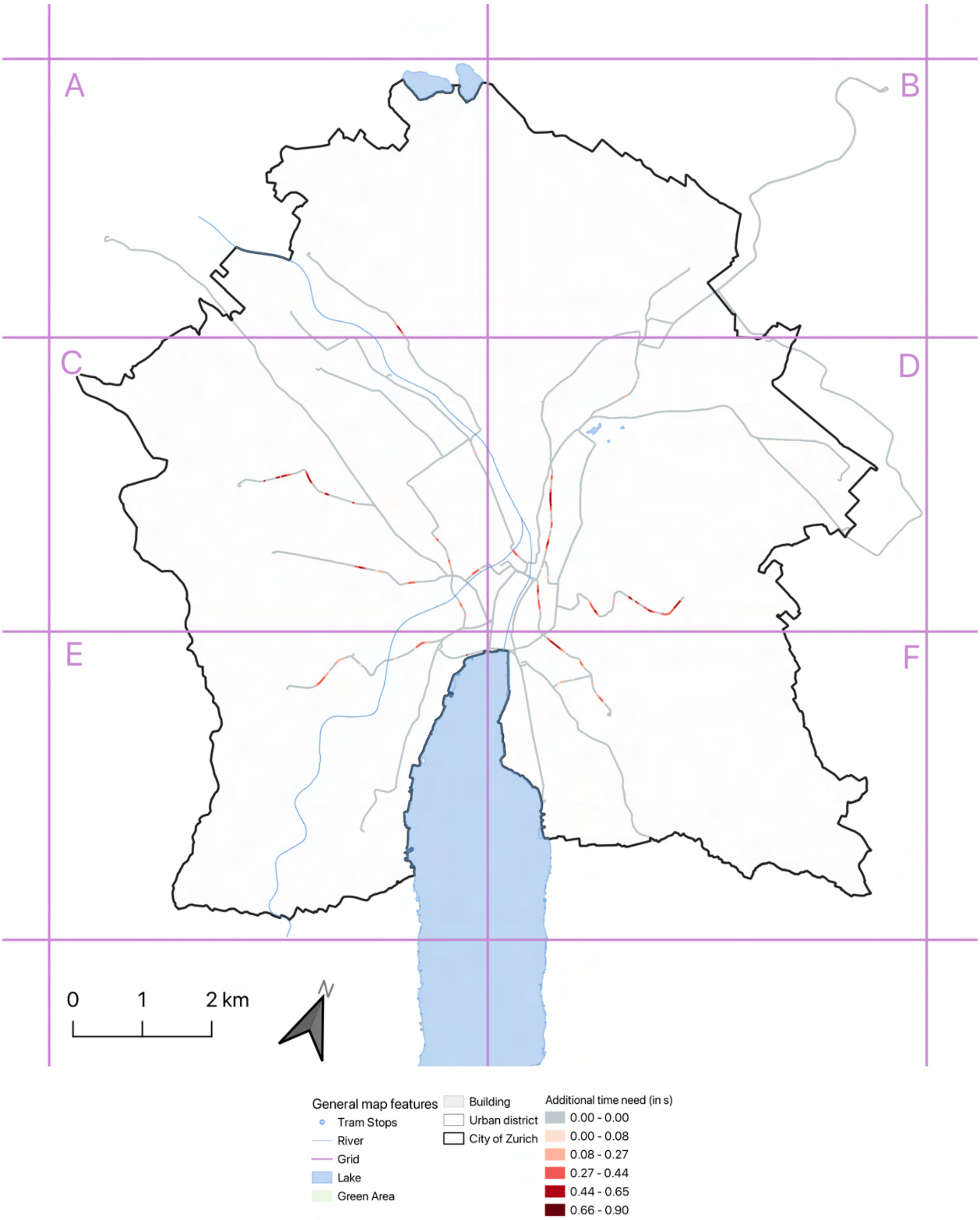


**Figure C.2:** Overview of the tram network during HVZ2 (Direction 2), displayed in 20-meter segments. The median additional time need (in seconds) are color-coded to show variations across the network. The grid system (labeled A–F) is used for reference.

### C.1.1 Close-up Views of the Tram Network (Direction 2)

#### Comparison of Additional Time Needed (in s) for Trams in Grid A during HVZ1 and HVZ2, Direction 1

Figures C.3 and C.4 show the additional travel time for trams in Grid A during HVZ1 and HVZ2, respectively, in 20-meter segments for Direction 2. The analysis reveals minimal differences between the two traffic periods, with very similar patterns of delay observed.

As in Direction 1 (Figures B.3 and B.4), the only segment exhibiting notable additional travel time is located between Schwert and Meierhofplatz. This observation is consistent across both directions and both traffic periods. No other segments with significant additional travel time were identified in Grid A for either direction, suggesting that delays in this area are localized and specific to this segment.

#### Comparison of Additional Time Needed (in s) for Buses in Grid B during HVZ1 and HVZ2, Direction 1

Figures B.5 and B.6 illustrate the additional travel time for buses in Grid B during HVZ1 and HVZ2, respectively, in 20-meter segments for Direction 1. The results show largely consistent patterns between the two traffic periods, with specific segments experiencing notable additional travel time in both HVZ1 and HVZ2.

Similar to Direction 1 (Figures B.3 and B.4), the segments between Siemens and Fellenbergstrasse, as well as between Hubertus and Altes Krematorium, exhibit the longest additional travel times in Direction 2. These segments are consistently highlighted across both HVZ1 and HVZ2.

A slight variation is observed in the segment between Siemens and Hubertus. During HVZ2, this segment falls into the highest delay class (0.63–0.93 seconds), while in HVZ1, no 20-meter segments reach this class. This indicates a slightly higher delay during HVZ2 for this specific segment. Additionally, a minor increase in additional travel time is noted for the segment between Güterbahnhof and Bäckeranlage during HVZ2, whereas no differences are observed for this segment during HVZ1.

#### Comparison of Additional Time Needed (in s) for Trams in Grid C during HVZ1 and HVZ2, Direction 2

Figures C.7 and C.8 depict the additional travel time for trams in Grid C during HVZ1 and HVZ2 in direction 2. The analysis reveals a high degree of similarity between the two primary traffic periods.

Significant hotspots with elevated additional travel time are observed between Strassenverkehrsamt and Uetlihof, similar to Direction 1 (See Figure B.7 and B.8).

Between Uetlihof and Laubegg there are additional time needs for both traffic periods, HVZ1 and HVZ2, where for HVZ1 there are slightly higher values in HVZ1 compared to HVZ2, whereas in direction 1 it is exactly the opposite. Also between Waffenplatzstrasse and Bahnhof Enge/Bederstrasse there is an additional time need with more consecutive 20m segments for direction 1.

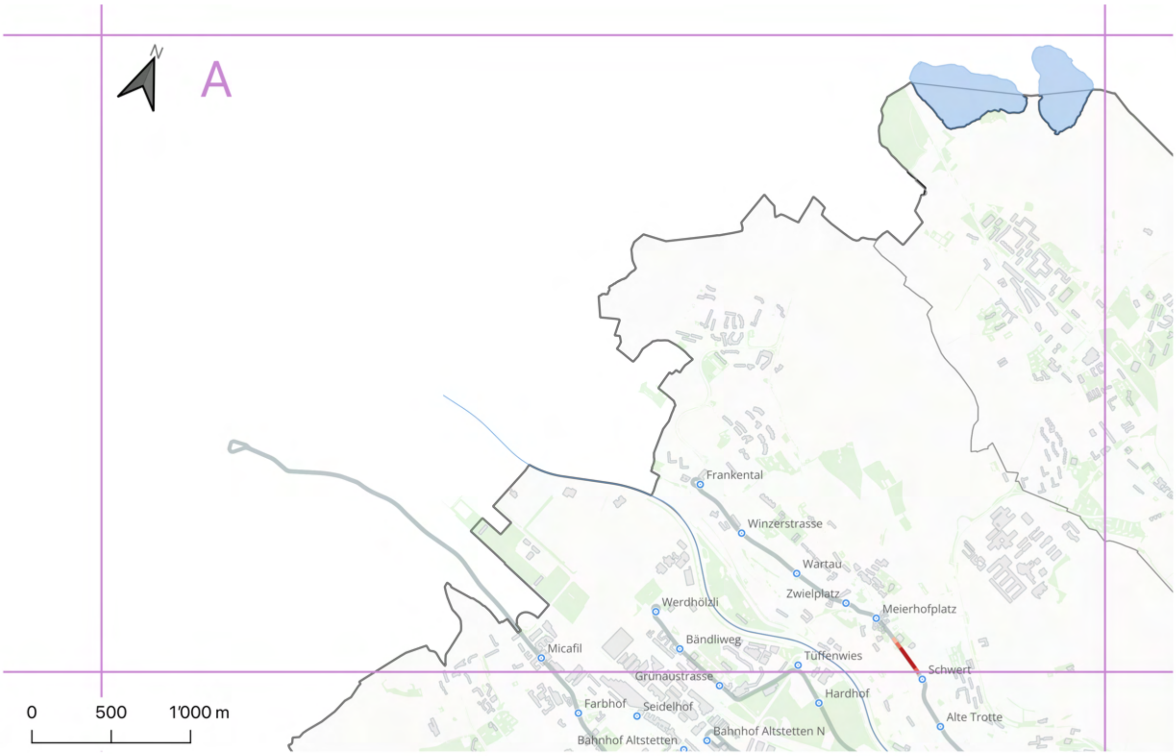


**Figure C.3:** Additional time need (in s) for trams in Grid A during HVZ1, Direction 2, in 20-meter segments. See Figure C.17 for detailed legend.

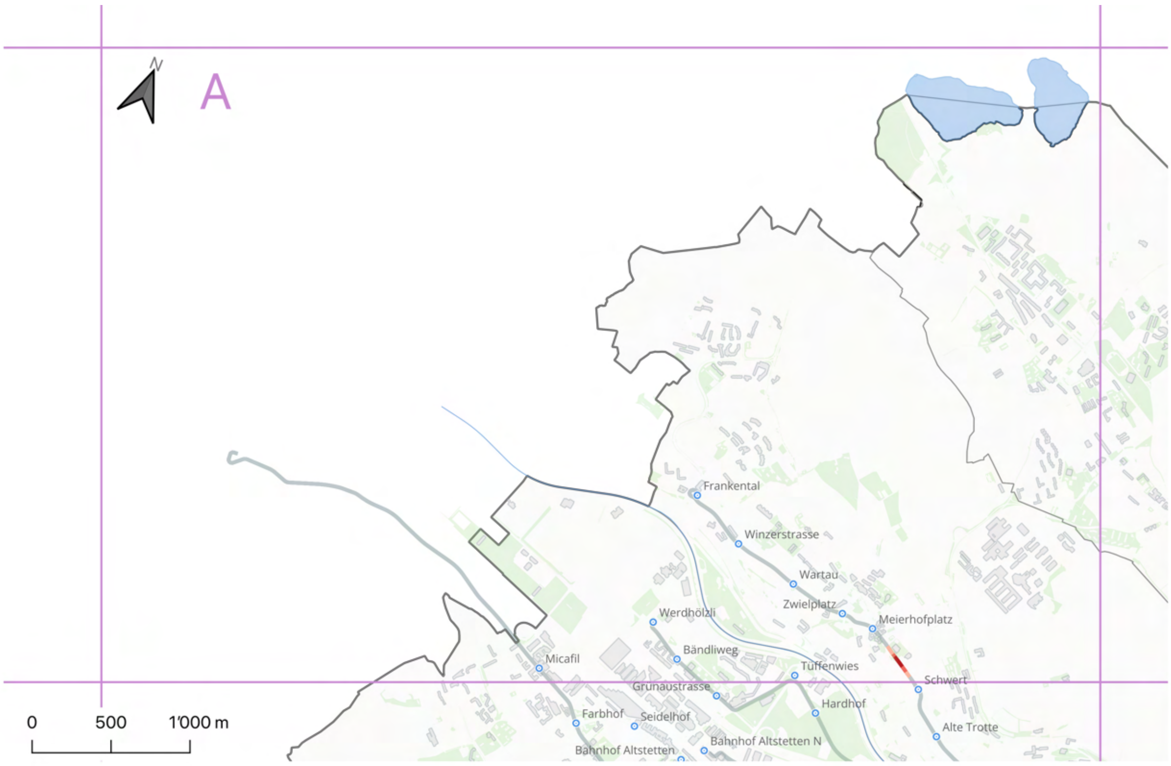


**Figure C.4:** Additional time need (in s) for trams in Grid A during HVZ2, Direction 2, in 20-meter segments. See Figure C.18 for detailed legend.


**Figure C.5:** Additional time need (in s) for trams in Grid B during HVZ1, Direction 2, in 20-meter segments. See Figure C.17 for detailed legend.


**Figure C.6:** Additional time need (in s) for trams in Grid B during HVZ2, Direction 2, in 20-meter segments. See Figure C.18 for detailed legend.

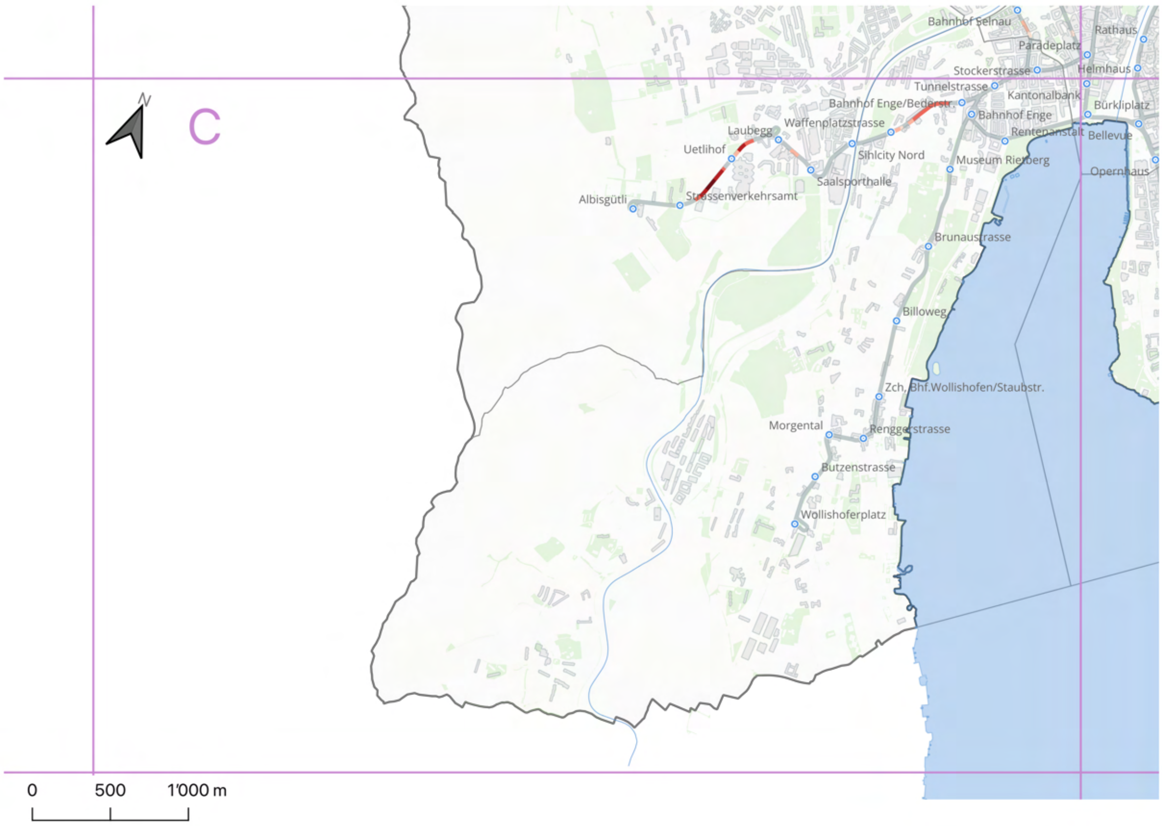


**Figure C.7:** Additional time need (in s) for trams in Grid C during HVZ1, Direction 2, in 20-meter segments. See Figure C.17 for detailed legend.

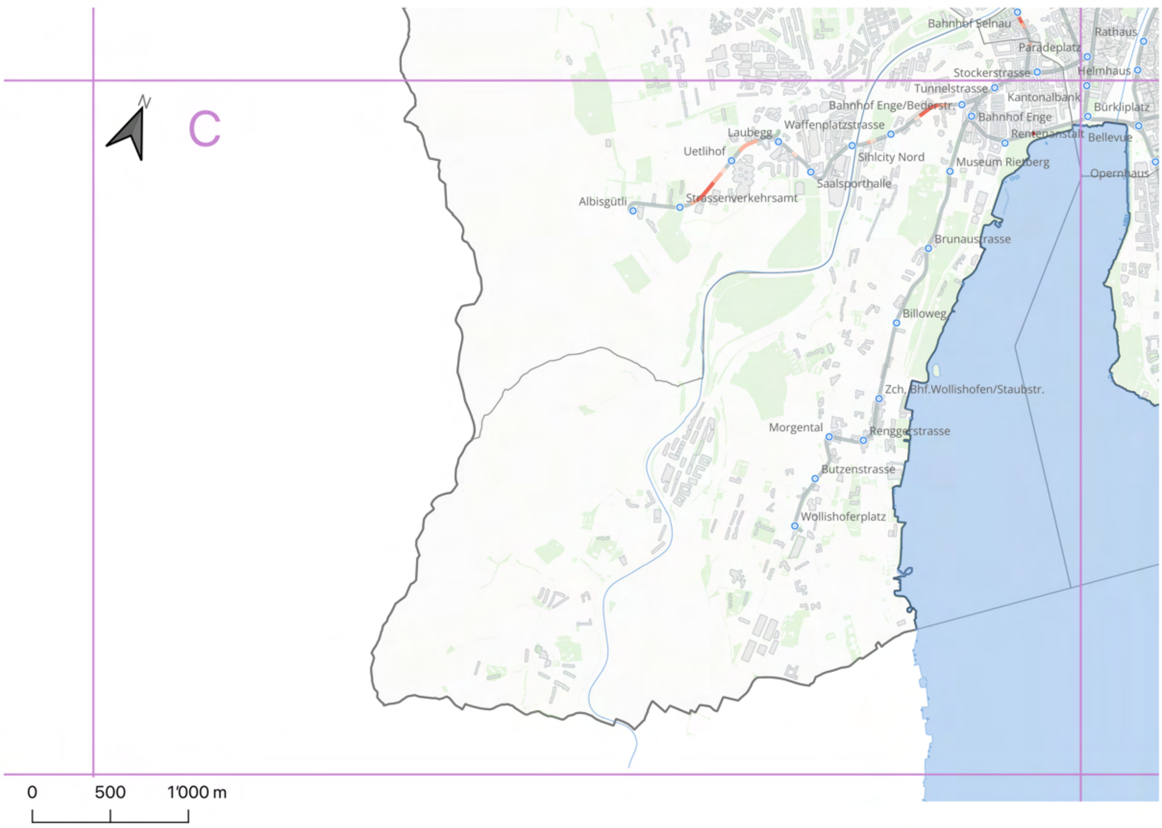


**Figure C.8:** Additional time need (in s) for trams in Grid C during HVZ2, Direction 2, in 20-meter segments. See Figure C.18 for detailed legend.

### Comparison of Additional Time Needed (in s) for Buses in Grid D during HVZ1 and HVZ2, Direction 1

Figures A.9 and A.10 depict the additional travel time for buses in Grid D during HVZ1 and HVZ2 in Direction 2. The analysis reveals no significant additional travel time in this grid for either traffic period. These findings are consistent with those for Direction 1 (see Figures 5.10 and 5.11).

This result suggests that bus operations in Grid D are largely unaffected during both HVZ1 and HVZ2. The absence of notable delays across both directions and traffic periods may indicate efficient traffic management or lower demand in this area.

### Comparison of Additional Time Needed (in s) for Trams in Grid E during HVZ1 and HVZ2, Direction 2

Figures C.13 and C.14 illustrate the additional travel time for trams in Grid E during HVZ1 and HVZ2 in Direction 2. The most affected segments include those between Röslistrasse and Ottikerstrasse, Ottikerstrasse and Soneggstrasse, as well as between Bahnhofplatz/HB and Neumarkt. These areas consistently show elevated additional travel times.

When comparing between HVZ1 Figure C.9 and HVZ2 Figure C.10 especially between Toblerplatz and Zoo the highest additional time need, HVZ2 show an additional time need up to 0.90, where in HVZ1 there are almost no changes in time compared to the median reference period.


**Figure C.9:** Detailed view of additional time need between stops Voltastrase and Zoo in HVZ1 Direction 2


**Figure C.10:** Detailed view of additional time need between stops Voltastrase and Zoo in HVZ2 Direction 2

### Comparison of Additional Time Needed (in s) for Buses in Grid F during HVZ1 and HVZ2, Direction 2

Figures C.15 and C.16 illustrate the additional travel time for buses in Grid F during HVZ1 and HVZ2 in Direction 2.

The greatest differences in travel time between the reference period and the speed adjustments introduced by the RNMP are observed between Kunsthaus and Hottingerplatz. This pattern is consistent with findings for Direction 1 (Figures B.13 and B.14). Additional delays are also noted between Hottingerplatz and Römerhof, as well as between Hölderlinstrasse and Klusplatz. These segments exhibit consistently higher travel times during both traffic periods, indicating localized impacts of the mitigation measures.

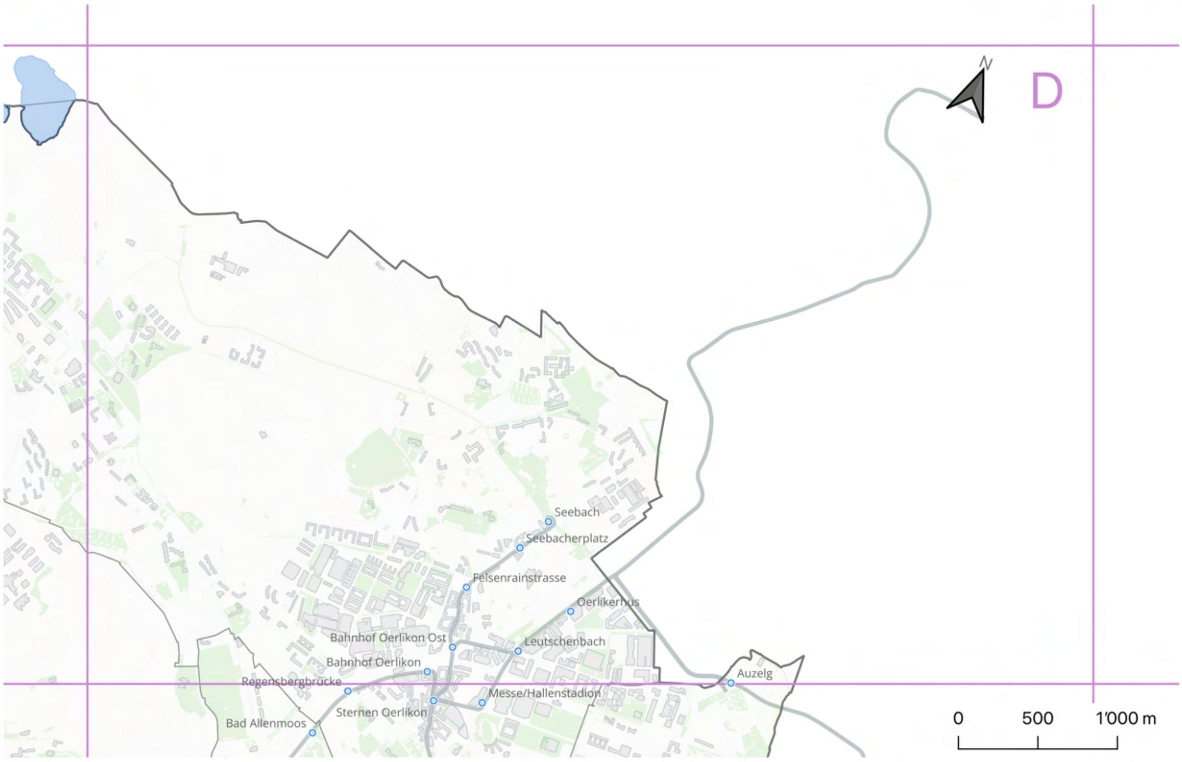


**Figure C.11:** Additional time need (in s) for trams in Grid D during HVZ1, Direction 2, in 20-meter segments. See Figure C.17 for detailed legend.

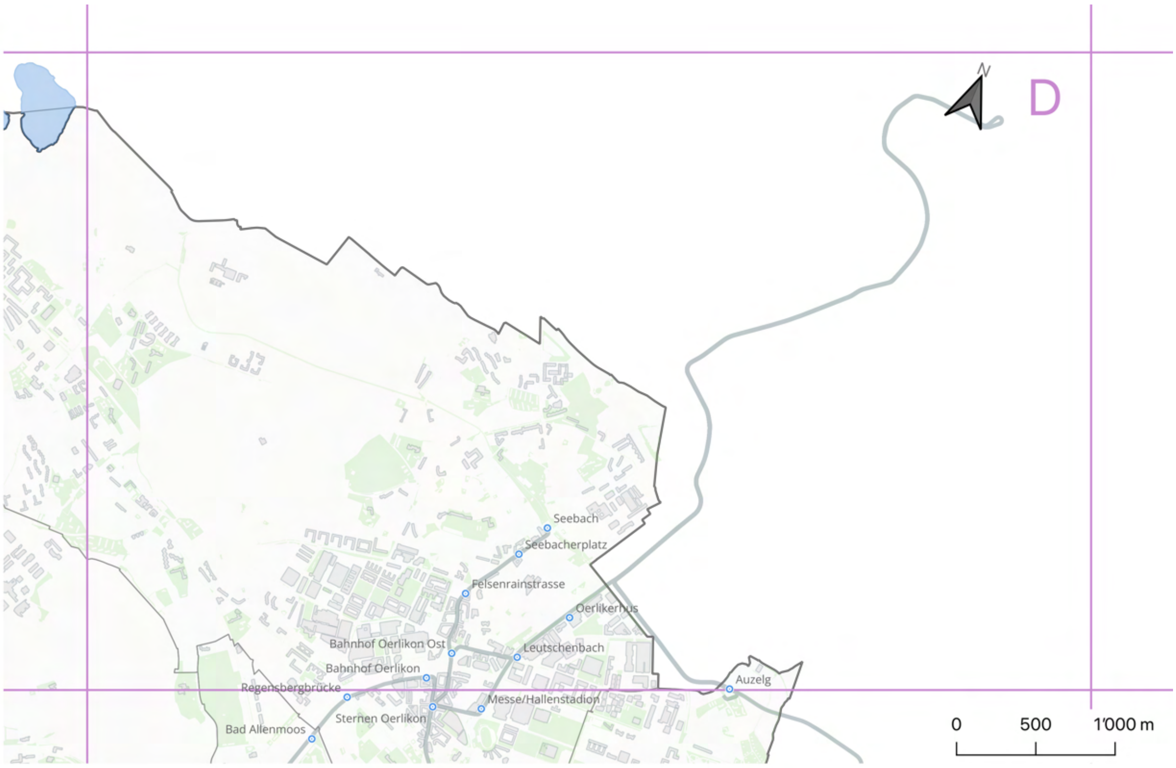


**Figure C.12:** Additional time need (in s) for trams in Grid D during HVZ2, Direction 2, in 20-meter segments. See Figure C.18 for detailed legend.

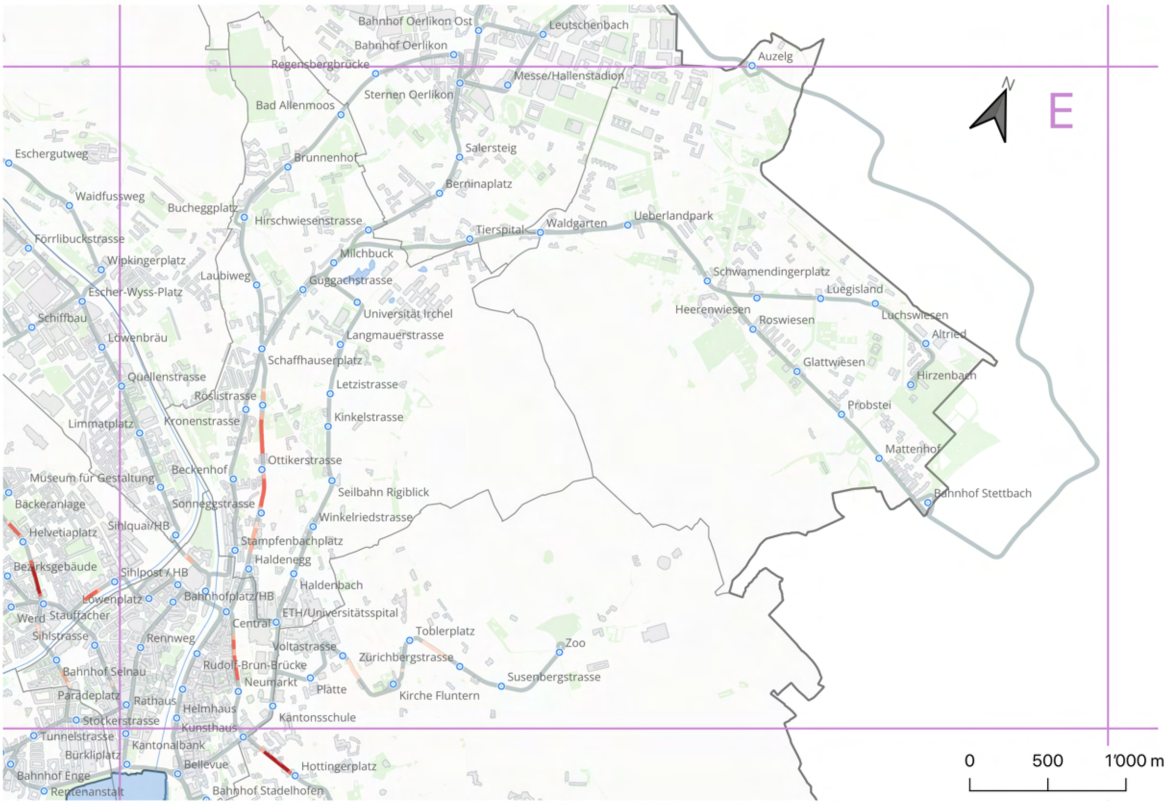


**Figure C.13:** Additional time need (in s) for trams in Grid E during HVZ1, Direction 2, in 20-meter segments. See Figure C.17 for detailed legend.

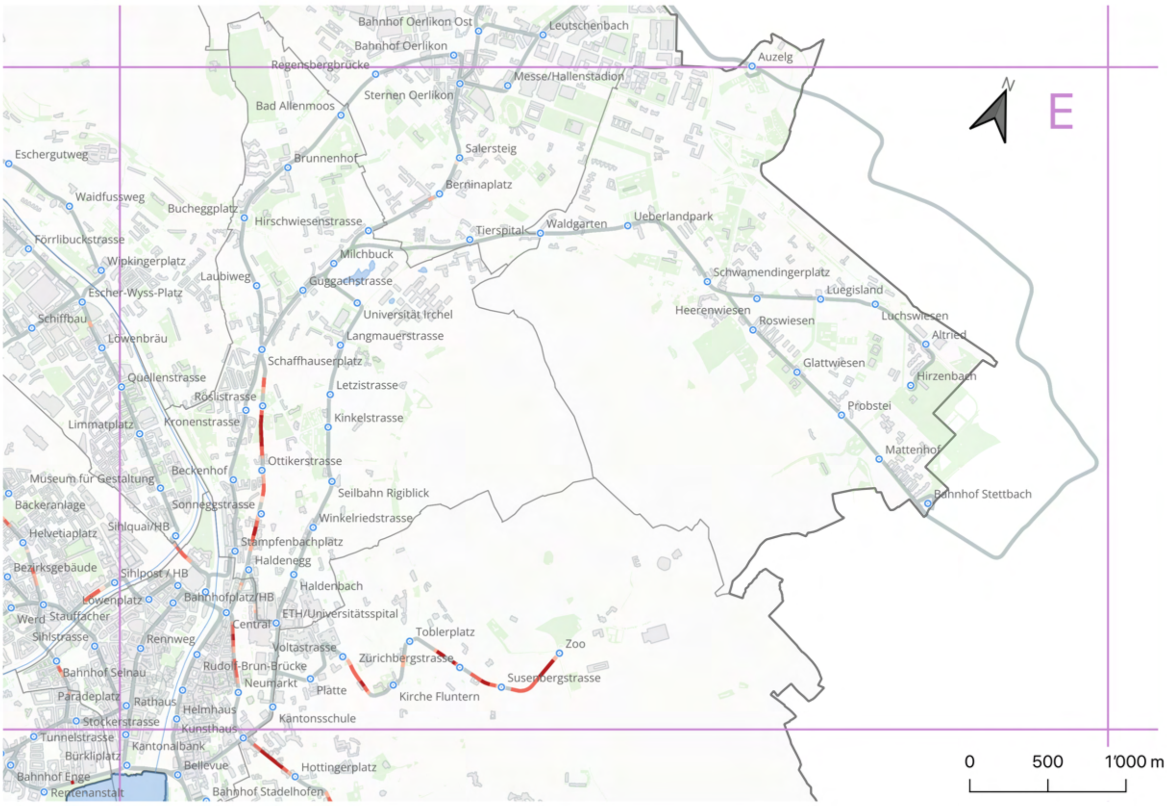


**Figure C.14:** Additional time need (in s) for trams in Grid E during HVZ2, Direction 2, in 20-meter segments. See Figure C.18 for detailed legend.


**Figure C.15:** Additional time need (in s) for trams in Grid F during HVZ1, Direction 2, in 20-meter segments. See Figure C.17 for detailed legend.


**Figure C.16:** Additional time need (in s) for trams in Grid F during HVZ2, Direction 2, in 20-meter segments. See Figure C.18 for detailed legend.

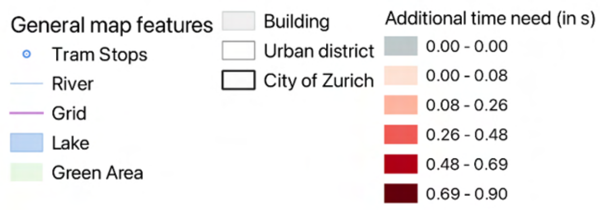


**Figure C.17:** Legend for tram in HVZ1 Direction 2 for grid A-F

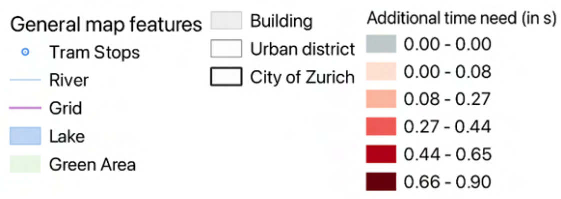


**Figure C.18:** Legend for tram in HVZ2 Direction 2 for grid A-F

# Chapter D

# Used R Packages

| Package | Version | Description |
|---|---|---|
| sf | 1.0-19 | Simple Features for R. |
| spdep | 1.3-8 | Spatial dependence: weighting schemes and statistics. |
| ggplot2 | 3.5.1 | Create elegant data visualizations using the grammar of graphics. |
| ggrepel | 0.9.6 | Automatically position non-overlapping text labels in ggplot2. |
| dplyr | 1.1.4 | A grammar of data manipulation. |
| raster | 3.6-30 | Geographic data analysis and modeling. |
| leaflet | 2.2.2 | Create interactive web maps with the JavaScript Leaflet library. |
| elevatr | 0.99.0 | Access elevation data from various APIs. |

**Table D.1:** Overview of R packages used in this analysis.

# Chapter E

# Personal declaration

I hereby declare that the submitted thesis results from my own independent work. All external sources are explicitly acknowledged in the thesis.

I further acknowledge that ChatGPT and other Wordvice.AI were utilized during the completion of this thesis to assist with grammar, syntax, and content refinement.

Zurich, January 31, 2025

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