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Operational Effects of Dedicated Bus Lanes

A Case Study Based on AVL and GTFS Data in Örebro, Sweden.

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ABSTRACT

Cities are increasingly addressing sustainable urban mobility by investing in dedicated bus lanes. While intended to improve public transport operations, the effectiveness of such measures varies by local context. Evaluating these impacts requires careful analysis using operational data.

This thesis presents a case study of dedicated bus lanes in Örebro, Sweden, analysing travel time and operating speed before and after Bus Rapid Transit (BRT)-inspired interventions. Service lines are compared based on their level of exposure to the dedicated corridor, allowing assessment of whether the benefits of such infrastructure depend on the extent of exposure. The analysis uses Automatic Vehicle Location (AVL) data from the GTFS-Realtime VehiclePositions feed. General Transit Feed Specification (GTFS) data provide route geometries for spatial matching. Data quality assurance addressed issues such as repeated position records from polling behaviour. Travel time and operating speed were summarised using median, standard deviation, and percentiles, with period-to-period changes tested for significance (Mann-Whitney U test) and mapped spatially at a 25-metre resolution.

Results show significant improvements in median travel time for all service lines and in operating speed for those with continuous exposure to the intervention. The scale of improvement correlates with exposure; fully exposed lines improved by about twice as much as partially exposed lines. Reliability gains were most pronounced for continuous exposure. Some improvements for partially exposed lines resulted from route realignments. Spatial analysis indicates that benefits varied along the corridor, with some sections experiencing greater effects than others.

This structured, reproducible approach integrates operational data with transport theory-based indicators to evaluate bus-priority effects at both network and section levels. The findings aim to provide practical insights and evidence to help urban transport planners design efficient, reliable public transport systems.

KEYWORDS

Dedicated bus lanes, Bus Rapid Transit, Public transport performance, Travel time variability, Operating speed, AVL data, GTFS data, Data quality assurance, Urban mobility, Before-after analysis, High-frequency bus services, Mann-Whitney U test.

SAMMANFATTNING

Städer arbetar i allt högre grad för att främja hållbar urban mobilitet genom investeringar i dedikerade busskörfält. Även om åtgärderna syftar till att förbättra kollektivtrafikens funktion, varierar deras effektivitet beroende på lokala förutsättningar. En noggrann analys av driftdata krävs för att utvärdera dessa effekter.

Detta examensarbete presenterar en fallstudie av dedikerade busskörfält i Örebro, Sverige, där restid och operativ hastighet analyseras före och efter BRT-inspirerade insatser. Linjer jämförs utifrån sin exponering för den dedikerade korridoren, vilket möjliggör en bedömning av om infrastrukturens nytta beror på exponeringsgraden.

Analysen använder AVL-data (Automatic Vehicle Location) från GTFS-Realtime VehiclePositions-flödet. GTFS-data (General Transit Feed Specification) används för att erhålla linjesträckningar för rumslig matchning. Datakvalitetssäkring har hanterat problem med upprepade positionsposter från pollningsbeteende. Restid och operativ hastighet sammanfattades med median, standardavvikelse och percentiler och förändringar mellan perioder testades för signifikans (Mann-Whitney U-test) samt kartlades rumsligt på 25-metersnivå.

Resultaten visar tydliga förbättringar i medianrestid för samtliga linjer samt i operativ hastighet för dem med kontinuerlig exponering för åtgärden. Förbättringens omfattning korrelerar med exponeringsgraden; fullt exponerade linjer förbättrades cirka dubbelt så mycket som delvis exponerade. Tillförlitligheten ökade mest för de kontinuerligt exponerade linjerna. Vissa förbättringar för delvis exponerade linjer berodde på omdragning av linjer. Rumslig analys visar att effekterna varierade längs korridoren, med vissa sträckor som uppvisade större förändringar än andra.

Detta strukturerade och reproducerbara tillvägagångssätt integrerar driftdata med indikatorer baserade på transportteori för att utvärdera effekterna av bussprioritering på både nätverks- och avsnittsnivå. Resultaten syftar till att ge praktiska insikter och underlag för stadsplanerare vid utformning av effektiva och tillförlitliga kollektivtrafiksystem.

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1 INTRODUCTION

Urbanisation and rising travel demand have intensified pressure on cities to develop efficient and sustainable transport systems. Prioritising public transport is recognised as a key way to alleviate congestion, reduce emissions, and improve urban accessibility. Dedicated bus lanes are one of the most common interventions to achieve these aims, as they can reduce travel times and improve service reliability. However, the effects of dedicated bus lanes are not uniform; they depend on local urban conditions and how they interact with existing infrastructure. This underlines the need for empirical, context-sensitive evaluation based on real-world data.

Örebro is selected as the case study because its urban structure and public transport challenges represent many medium-sized cities facing similar pressures. Studying Örebro makes it possible to develop and test a structured, data-driven evaluation method that can be useful for other cities in comparable situations. By focusing on this real-world example, the thesis demonstrates how dedicated bus lanes can affect bus operations in practice.

1.1 BACKGROUND

In Sweden, bus-priority measures align with national transport policy objectives, which aim to ensure an economically efficient and sustainable transport system for citizens and businesses nationwide (Regeringskansliet, n.d.). Consequently, numerous cities are investing in infrastructure improvements for public transport, often drawing on principles of Bus Rapid Transit (BRT) systems:

BRT is a set of design and operational principles intended to enhance the speed, reliability (the consistency of service from one day to the next), and capability of bus services. Core components typically include dedicated bus lanes, signal priority, efficient boarding systems, and improved station design. While some regions implement comprehensive BRT corridors, many European cities adopt these elements incrementally, contingent on spatial and budgetary constraints.

Örebro exemplifies this incremental approach. Since 2020, the city has implemented BRT-inspired measures in phases, including dedicated bus lanes, signal prioritisation, and redesigned bus stops (Region Örebro, 2026). This staged implementation produces varying impacts across routes

and corridor sections (the specific stretches of road along the studied bus route), making the effects both complex and highly dependent on local context. Detailed Automatic Vehicle Location (AVL) data enables analysis of operational performance before and after interventions. AVL data consists of GPS-based records that capture each bus's movements, such as position, timestamp, and vehicle identification (Ohio State University, 2026), and this study receives it through the `VehiclePositions` stream of the GTFS-Realtime (GTFS-RT) specification (a continuously updated feed of live vehicle positions). GTFS-RT is an extension of the General Transit Feed Specification (GTFS), a standardised format that enables public transit agencies to describe their services, including schedules, routes, stops, and fares, in a manner accessible to a broad array of software applications (GTFS, n.d.). In practice, GTFS therefore consists of two complementary parts: a static component describing the planned, published schedule and network, and a real-time component, of which `VehiclePositions` is one type. AVL data provide the operational basis for this study, while route geometries (the geographic shape of each bus route, used to map GS positions onto a specific stretch of road) from the static GTFS feed define the corridor and assign observations to bus lines. This study does not use stop and timetable information from GTFS or the GTFS-RT `TripUpdates` stream; instead, it relies on a before-and-after comparison of AVL-derived operational data between the two measurement periods.

By integrating these datasets, researchers can directly compare scheduled operations with actual bus behaviour. AVL technology installed on buses interacts with GPS satellites to track vehicles' locations in real time. This real-time data supports research, education, and day-to-day operational monitoring, such as evaluating service reliability and identifying congestion patterns (Ohio State University, 2026). As an open standard, GTFS makes transit data universally accessible (GTFS, n.d.).

This study is conducted in collaboration with Linköping University, WSP, and the Czech Technical University. WSP's involvement reflects a practical interest in developing data-driven evaluation methods that can support real-world transport planning and decision-making.

1.2 AIM OF THE STUDY

This thesis aims to evaluate the impact of dedicated bus lanes on operational performance in Örebro, using AVL and GTFS data. It also seeks to develop a quantitative method applicable to similar urban settings.

To achieve this, the study is structured in several steps. First, the study identifies relevant methods and performance indicators from previous research and adapts them to high-frequency bus services. Second, the study collects and processes AVL and GTFS data, including systematic data quality assurance to ensure the analysis is based on reliable observations. Third, operational performance is evaluated through a before-and-after comparison of selected indicators, focusing on travel time, speed, reliability and variability. Finally, the results are analysed at both the section and corridor levels to understand where and how effects occur.

By combining methodological and empirical development with an empirical case study, the study seeks to generate insights that are both analytically rigorous and practically relevant to transport planning.

1.3 RESEARCH QUESTIONS

Three overarching research questions guide the study:

RESEARCH QUESTION 1: *What are the operational effects of dedicated bus lanes in Örebro?*

This question is addressed by examining how the bus lanes affect travel times, operating speed along the corridor, and service reliability, and by comparing how these effects differ between corridor sections with varying degrees of exposure to the intervention.

RESEARCH QUESTION 2: *How can GTFS data be applied and validated to ensure reliable analysis of bus operations?*

Answering this involves determining how to process, combine, and align the different data sources; what quality assurance measures are needed to ensure completeness, consistency, and validity; and how to account for any remaining data limitations or uncertainties when interpreting the results.

RESEARCH QUESTION 3: *How can a robust evaluation method be developed to assess the effects of dedicated bus lanes using operational data?*

This is explored by identifying which quantitative methods from previous research suit high-frequency bus services, which performance indicators best capture changes in speed, reliability, and variability, and how to derive these indicators systematically and reproducibly from GTFS data.

1.4 APPROACH

This thesis assumes, supported by previous research, that dedicated bus lanes improve bus operations by reducing interactions with mixed traffic and signal delays (Levinson et al., 2003). These effects typically show up as changes in travel time, operating speed, reliability, and variability, which are also central performance indicators in BRT assessment frameworks (ITDP, 2026a; 2026b).

Because high-frequency bus services are particularly sensitive to operational disturbances, the evaluation prioritises travel time variability metrics (i.e., how much travel times fluctuate from trip to trip), rather than only their average value). Measures of central tendency (median) are complemented by dispersion-based indicators, such as standard deviation and percentiles, to capture both typical and worst-case operating conditions.

The analysis is observational and retrospective, relying on historical AVL and GTFS data. AVL provides detailed physical movement records, while GTFS offers scheduled information (Trafiklab, 2026b). To ensure the evaluation is based on complete and consistent observations, the approach incorporates systematic data quality-assurance procedures, including checks for missingness, consistency, and structural validity.

The workflow follows the sequence shown in *Figure 1:1*: data collection, filtering, quality assurance, metric computation, and comparative evaluation. Identical analytical procedures are applied to both before- and after-implementation datasets to ensure methodological consistency.

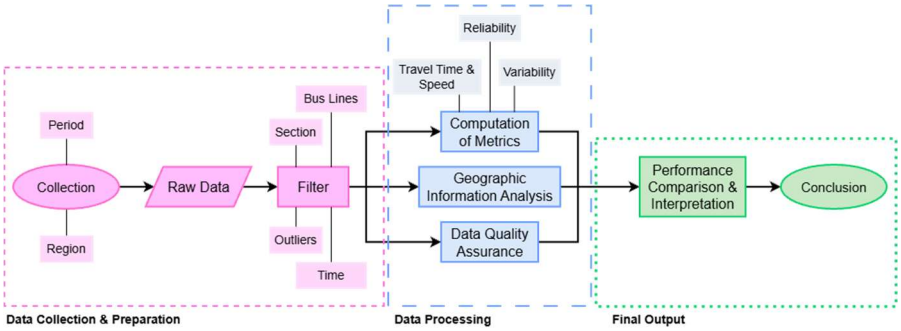


Figure 1:1. Flowchart of the thesis method.

The workflow proceeds through several key stages, as illustrated in *Figure 1:1:* data collection, filtering, quality assurance, metric computation, and comparative evaluation. The same analytical procedures are applied to both the before- and after-analysis datasets to maintain methodological consistency.

This workflow follows the logical relationships between steps. To ensure accurate results, raw GTFS data are initially filtered by period, section, bus line and time. This step is crucial, as unfiltered or misaligned data could distort estimates of travel time, speed, and reliability. Filtering by these dimensions enables the analysis to be broken down by corridor section and time window, which is essential for understanding how the bus lane's effects differ along the route. Geographic information analysis and data quality assurance are integrated with the metric computation process, rather than treated as separate, subsequent steps. This approach recognises that spatial matching and quality checks directly influence metric deviation and should not be treated as independent stages. By applying identical procedures to both before- and after-analysis datasets, the analysis ensures that any observed performance differences can be confidently attributed to the bus lane intervention itself, rather than to methodological variation.

AI-based writing (Grammarly) and reference-support tools (Microsoft Copilot) were employed solely for linguistic refinement, literature organisation and sanity checks for programming code. Analytical procedures, methodological decisions, and all interpretations remain entirely independent and academically grounded.

1.5 LIMITATIONS

This study draws on one week of data per year (October 2023 and October 2025) to examine a BRT implementation that remains a work in progress. At the time of analysis, Phase 2 had not yet begun, and several Phase 1 sections were completed only recently. As a result, the findings reflect a brief observation period and an early stage of operations, rather than the system's eventual, stabilised performance.

This study also pools all days within each one-week period without distinguishing weekdays from weekends. Because weekday and weekend travel patterns typically differ in both volume and congestion timing, this aggregation may mask distinct trends within each period.

The results focus exclusively on the segments of each service line within the designated study corridor; performance outside this area was not considered. The Trunk and Small Trunk categories indicate how much each line's route overlapped with the corridor, a factor that shifted between 2023 and 2025 as routes were redrawn during the ongoing BRT implementation. Like other single-corridor case studies, these findings are particular to the context of Örebro and this specific corridor.

Since route alignments were revised as part of the very BRT implementation under evaluation, it is not possible to fully disentangle the effects of genuinely improved operational speeds from the impact of measuring shorter routes on observed travel time changes. This limitation arises because the intervention simultaneously altered both infrastructure and route layouts.

This thesis relies exclusively on physically observed AVL data (vehicle positions) and omits schedule-based data or static timetables. While this approach avoids tying the analysis to potentially shifting schedules over the two study periods, it also means that indicators like on-time performance fall outside the scope of the present study.

As discussed in *Section 4.2*, it was not possible in this thesis to distinguish scheduled buffer (recovery) time from regular dwell time or unplanned delays. The AVL data captures only the vehicle's position, time, and bearing, without indicating operational status, and the GTFS static data for the corridor lacked detailed stop-level arrival and departure times needed to identify buffer time. As a result, some of the recorded travel and dwell times may reflect planned schedule adherence rather than actual operating

conditions. This limitation should be considered when interpreting the travel time and reliability results presented here.

The completeness threshold used to filter incomplete trips (*Section 5.2.1*) was set based on exploratory inspection of the distribution of grid cells covered per trip, rather than derived from prior literature or formal sensitivity testing. A different threshold could plausibly yield somewhat different trip inclusion and results; this sensitivity was not formally assessed.

2 BACKGROUND & CASE STUDY

This Section presents the study context by introducing Örebro as a case for analysing the effects of bus-priority measures. The focus is on key features of the city (such as its size and recent public transport initiatives) that make Örebro a relevant example for similar urban environments. The Section also briefly describes the implementation of Bus Rapid Transit (BRT)-inspired measures in Örebro.

The case study approach grounds the research in a real-world context and enables assessment of the effects of dedicated bus lanes using observed data.

The section first introduces BRT and its application in Sweden. It then gives a focused overview of Örebro, emphasising why the city is suitable for the study. The Section concludes with a summary of the BRT-inspired measures implemented in Örebro and a description of the data sources used.

2.1 BUS RAPID TRANSIT IMPLEMENTATION

Bus Rapid Transit (BRT) is a public transport concept that aims to make urban mobility faster, more reliable, and more accessible for a wide range of people. By blending the flexibility of buses with features common to rail-based systems (such as dedicated lanes, priority at intersections, and thoughtfully designed corridors), BRT seeks to address everyday urban challenges (Cervero, 2013; Hidalgo & Muñoz, 2014). BRT partly emerged in response to congestion and the high cost and slow implementation of traditional rail projects, offering a practical, adaptable solution that can be introduced incrementally.

BRT is a concept implemented worldwide, ranging from fully separated corridors to systems in which only some elements are integrated. In Europe, many cities have adopted high-service bus systems that weave BRT features into established transport networks to better match how people travel (Cervero, 2013; Hidalgo & Muñoz, 2014). This incremental, context-sensitive approach is especially relevant for medium-sized cities like Örebro, where adaptations must fit local environments and needs.

Research shows that BRT systems that meet higher international standards achieve greater efficiency, reliability, and ridership, underscoring the value

of comprehensive system design (Levinson et al., 2003; Stewart et al., 2017). Branding, simplicity, and service priority are also central to user perception and attraction (Hess & Bitterman, 2008). This study focuses on how BRT concepts are adapted to the Örebro context, rather than applying generic frameworks. The next section briefly outlines how these principles are applied in Sweden, with a focus on Örebro.

2.1.1 INTERNATIONAL STANDARD

BRT is often described using the ITDP framework, which is widely recognised in research and practice as an international reference for defining and evaluating BRT systems (ITDP, 2026a). The ITDP definition sees BRT as a set of coordinated measures to improve speed, reliability, and passenger experience compared to regular bus services (ITDP, 2026a; Levinson et al., 2003).

The ITDP standard classifies BRT corridors based on design and operational features, awarding points for elements such as dedicated lanes, high-quality stations, and service planning. The total score determines the corridor's rating (ITDP, 2026b).

For this study, the ITDP framework is used primarily as a reference to clarify which BRT elements are relevant to the Örebro case, rather than as a strict evaluation tool.

2.1.2 NATIONAL STANDARD

The ITDP standard inspires the Swedish national guidelines but uses two levels – Green (full implementation) and Yellow (partial implementation) – and explicitly considers the urban environment (SKR, 2022; X2AB, 2015).

In Örebro, BRT is designed for high visibility, frequent service, and intersection priority (Region Örebro County, 2015). Around 75% of the system's sections meet the green level, showing that Örebro largely fulfils the national BRT criteria, as shown in *Table 2:1* below (the fully graded table is in *Appendix A*).

Table 2:1. Grade of each subsection of the national BRT standard in Örebro (Region Örebro County, 2015).

Subsection	Grade
Urban development	Yellow Level
Public Transport Infrastructure	Green Level
Vehicle and Support System	Green Level
Operations	Green Level

Örebro's BRT includes dedicated lanes, recognisable stations, frequent service, and off-board ticketing – features shown to boost speed and passenger satisfaction (SKR, 2022; Levinson et al., 2003).

Örebro uses distinctly coloured bus lanes to improve visibility and system identity (ITDP, 2026b). However, local conditions (such as snow and winter darkness) require more maintenance and special anti-slip measures.

2.2 ÖREBRO

The case study region was chosen because GTFS Regional data is available (Trafiklab, 2026a) and because information on local bus lane development is accessible.

Örebro – a medium-sized city in central Sweden – was selected. Its population size of around 160,000, its geographical importance, and available transport data make it suitable for this study (Örebro Municipality, 2026; SCB, n.d.).

2.2.1 SECTIONS OF IMPLEMENTATION

Since 2020, Örebro has seen significant developments in public transport. It is implementing BRT in two phases; the first phase, including all relevant sections, is shown in *Figure 2:1* below.

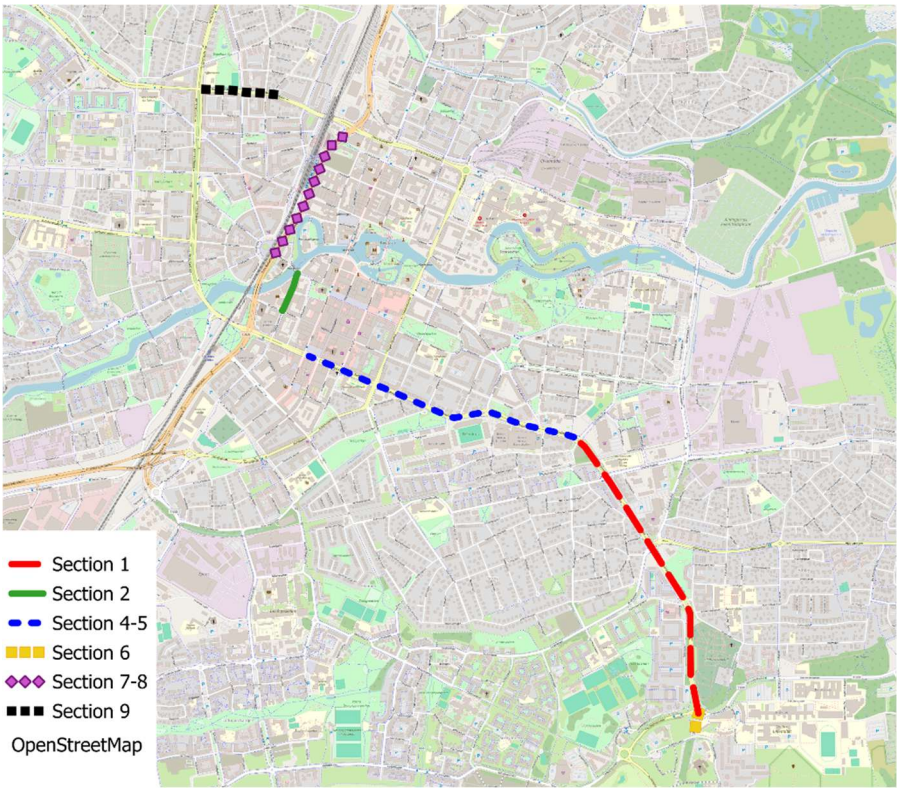


Figure 2:1. Relevant sections in Phase 1 in Örebro.

Phase 1 is completed and consists of nine sections (see *Figure 2:1*). Analysing the implementation in distinct phases is important because it allows the study to compare operational effects before and after each intervention, and to assess how specific changes – such as new lanes or signal priority – impact bus performance over time. A timeline of these building phases is shown in *Figure 2:2* below.

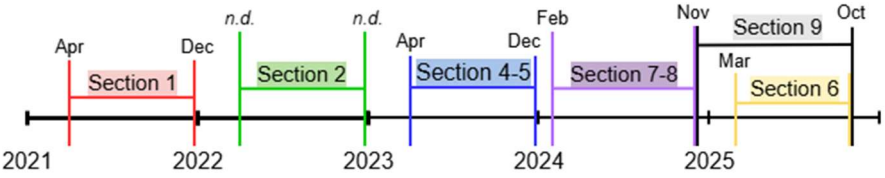


Figure 2:2. Timeline of the building phases in Phase 1.

The first section (red long-dashed line in *Figure 2:1*) was completed in 2021, and the changes included implementing two red-coloured bus lanes

in the centre of the road, one in each direction. A new bus stop design featuring a dry-grass roof was implemented. All the traffic lights were adjusted to prioritise public transport, a new accessible walking passage was installed, and new lighting was installed (Region Örebro County, 2026).

The second section of the phase (the green full line) consisted of implementing new bus stops adapted to the newer, faster bus lines, added passenger information that tells how long it is until the bus arrives, bus lanes were coloured red, the bike path was elongated, bicycle parking was added, and greenery was added. The entire section is dedicated to buses, not to private vehicles (Region Örebro County, 2026).

Section three consisted only of changes to the bus stop design (Region Örebro County, 2026); therefore, it was not deemed relevant to this thesis and was not shown in *Figure 2:1* or discussed in this section.

Sections four to five were completed in the year 2023. The implementation included centre-aligned bus lanes between two areas, new bus stops with weather protection and a dry-grass roof, improved lighting, new passenger information on bus arrivals, bicycle parking, a new pedestrian crossing, a new walking passage, and the removal of the bus stop Trädgårdsgatan (Region Örebro County, 2026).

The sixth section of the phase was completed in 2025; it continues section one. The section was remade into a bus street; the traffic lights were re-optimised to prioritise public transport. In one segment, a bus lane was implemented and painted red, and the bus stop Rundstigen was removed (Region Örebro County, 2026).

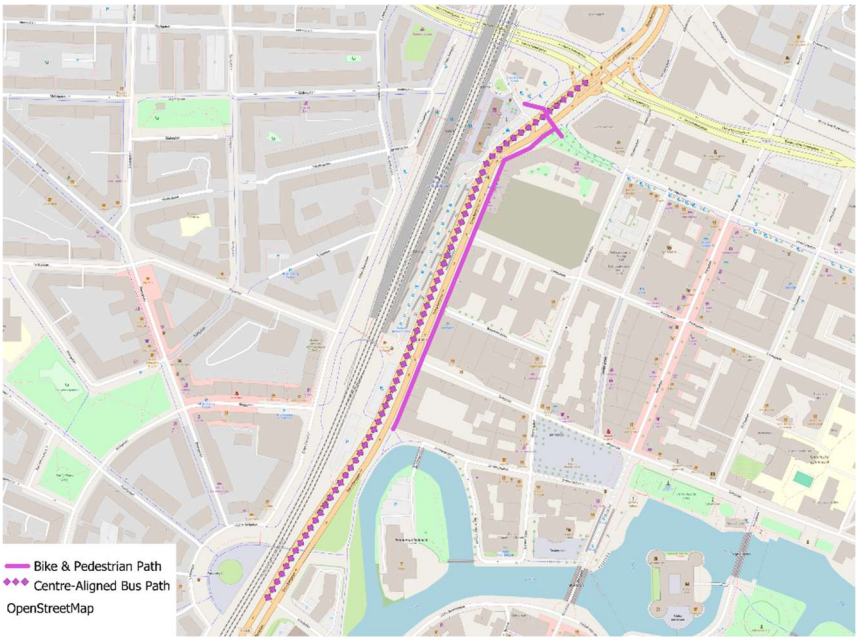


Figure 2:3. Section 7-8 in Phase 1 of Implementation of BRT in Örebro.

The seventh and eighth sections were completed in 2024 (see *Figure 2:3* above). A centre-aligned bus lane was implemented in the northbound direction and painted red (purple diamond segment); traffic signal prioritisation and a new pedestrian passage were also implemented (purple line). A new bicycle-and-pedestrian path (purple line) was built, and the lighting was improved, along with additional greenery (Region Örebro County, 2026).

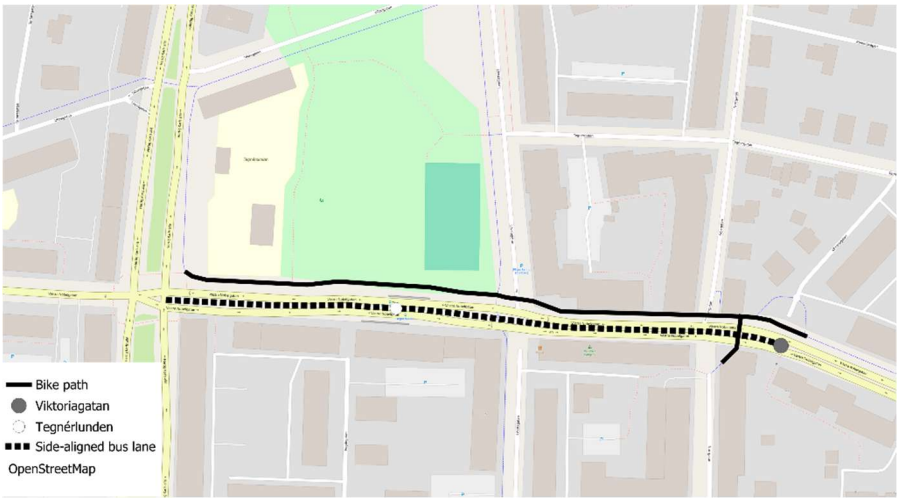


Figure 2:4. Section 9 in Phase 1 of Implementation of BRT in Örebro.

The last section of this phase, section 9, was completed in 2025 (see *Figure 2:4* above) and involved implementing a new bus stop at Tegnérlunden (white dot) with benches, lighting, weather protection, and a dry-grass roof. Side-aligned dedicated bus lanes were implemented, together with traffic signal prioritisation (black square line). Along this lane, new pedestrian and bike paths were built, and a crossing at Norrgatan (black line) was added with better lighting. New trees were planted alongside this section. Lastly, the stop at Viktoriagatan (grey dot) was removed (Region Örebro County, 2026).

2.3 Available Data

This study uses historical AVL data for Örebro, focusing on one week in October in 2023 and 2025, to answer the research questions regarding the effects of bus lanes on operational performance (data source and retrieval details are described in *Section 5.1.1*). Data selection focused on reliability and coverage across the relevant sections and time periods. The spatial and temporal scope was deliberately limited to ensure that the analysis reflects the locations and time windows most affected by the intervention, and where data quality is highest. Initial data collection resulted in 125,927,769 AVL observations across the full Örebro network for the two study weeks. After spatial filtering to the study corridor (*Section 5.2.2*), 1,297,982 observations remained, a reduction of about 97%. Although this resulted in a relatively small share of the original dataset, this focus increases the

validity of the findings for the studied corridor and aligns with the aim to identify causal effects of bus lane implementation. *Figure 2:5* illustrates the study area relative to the full dataset; the black dots show all buses in Örebro city, both public transport and replacement traffic for rail transport.

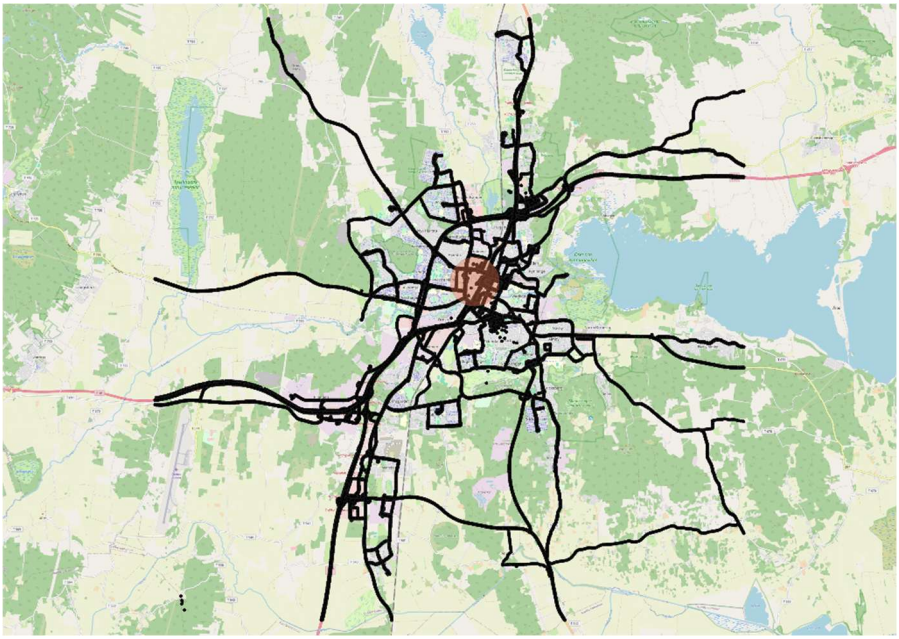


Figure 2:5. All Vehicle Positions for both years, together with the approximate area of study.

Real-time Automatic Vehicle Location (AVL) data from the GTFS-RT feed enabled reconstruction of detailed vehicle trajectories and operational metrics, providing an objective basis for evaluating performance before and after bus lane implementation.

Sections 7-9 were selected because they were constructed after the database began collecting data and underwent relevant BRT interventions. Analysing these sections, both separately and together, made it possible to isolate the local effects of specific measures and assess corridor-wide impacts – directly addressing the research questions about how bus lanes affect operational performance at different spatial scales. Two batches of bus lines were selected (see *Section 5.1.3*): one in which the bus lines operate continuously through the entire study area, called Trunk, and another batch with partial exposure to the study area, called Small Trunk. The analysis of bus lines in the Trunk assesses the full effects of the interventions, while

the Small Trunk bus lines were included for comparison. This design enables a direct test of whether the benefits of bus lanes depend on full or partial exposure – an aspect central to the research questions about spatial extent of intervention effects.

Analyses were performed for the morning peak, afternoon peak and night hours to capture both peak and off-peak performance. This temporal breakdown allows for a nuanced assessment of whether bus lane effects vary with demand and congestion, as posed in the research questions.

The evaluation (the third stage in *Figure 1:1*) proceeded in two steps: first, analysing bus lines with full exposure to the study area and bus lines with partial exposure; and second, comparing the results to pinpoint where and when bus lanes deliver improvements or reveal trade-offs.

3 LITERATURE REVIEW

The literature review will focus on travel behaviours and bus lane designs, then move to bus priority measures: their role in improving mobility, reliability, and sustainability in urban transportation; and lastly, data quality assurance: defining the concept and how to implement it.

3.1 PUBLIC TRANSPORT TRAVEL PATTERNS

Understanding travel behaviour is crucial because changes in travel time or reliability (key outcomes of bus lane interventions) directly affect why people choose public transport. Research shows that attributes like travel time, reliability, and frequency are as important as cost or comfort in mode choice, especially for buses in mixed traffic (Soza-Parra et al., 2022). Therefore, this thesis uses indicators such as reliability and travel time to assess how bus lanes affect the factors that matter most to passengers.

Dedicated bus lanes are expected to reduce exposure to congestion while improving travel times and reliability, two key indicators for evaluating the effects of interventions in this thesis. While previous studies, such as Arhin et al. (2022), confirm these benefits, particularly in congested corridors, reliability is not a single metric. Instead, it encompasses multiple dimensions, each capturing different aspects of service consistency and predictability.

3.2 PUBLIC TRANSPORT'S DESIGN & EFFECTS

High-frequency, easy-to-use routes and accessible stops can amplify the positive effects of bus lanes. These system design elements are considered when interpreting the results in Örebro (SKR, 2022; Redman et al., 2013).

One widely adopted bus priority measure is bus segregation, in which a specific region of the road (either at the side or in the centre) is reserved exclusively for buses (Dadashzadeh & Ergun, 2018). The precise design of these lanes is adapted to local circumstances. Side-aligned bus lanes may also accommodate bicycles, mopeds, and taxis, depending on their width. This arrangement facilitates overtaking and minimises obstructions for buses (SKR, 2022). Alternatively, centrally located bus lanes offer several advantages: they avoid conflicts with parked vehicles, prohibit access to

bicycles, taxis, and mopeds, and ensure that bus stops do not impede pedestrian pathways (SKR, 2022).

Empirical research shows that bus lanes and stop consolidation can cut average travel times, with the largest effects in congested environments (Keolis Sverige, 2020; Arhin et al., 2022; El-Geneidy et al., 2006).

3.3 AVL & GTFS Data in Transit Analysis

Much of contemporary research on public transport performance draws on detailed operational data, especially AVL and GTFS datasets. Access to these data sources enables examination of service operations at the level of individual trips and stop events. This, in turn, helps researchers better understand the variability and disruption patterns often hidden in aggregated statistics.

AVL data provide continuous, time-stamped vehicle positions, enabling researchers to reconstruct trajectories, identify delays, and analyse behaviour at individual stops. This level of detail is foundational for empirical studies of bus reliability and service consistency. GTFS-RT data describes the planned service and enables comparison with realised operations. These data sources ensure that performance indicators are based on observed (not just scheduled) data (Strathman & Kimpel, 2003; Aemmer et al., 2022; Liu et al., 2023). While much of this literature combines AVL with schedule-linked GTFS-RT data (`TripUpdates`) to compare observed against scheduled performance, this thesis relies solely on AVL/`VehiclePositions` data for its operational indicators, using GTFS static data only to derive route geometries.

For high-frequency bus services, headway-based analysis is particularly common because it can be used without consulting timetables. Metrics such as standard deviation are frequently used to assess regularity and reliability (Strathman & Kimpel, 2003; Bajić et al., 2022).

Travel time measures – including mean, median, and percentile-based statistics – capture both typical and extreme conditions. This thesis uses these indicators to assess whether bus lanes improve not only average performance but also robustness under congestion (Berkow et al., 2009; Büchel & Corman, 2020).

A before-and-after comparison of key indicators is used to isolate the effects of bus lane implementation (Aemmer et al., 2022; Liu et al., 2023).

3.4 PERFORMANCE INDICATORS

Performance indicators capture efficiency, reliability, and passenger experience. This thesis focuses on changes introduced by bus lanes, as identified in the theory and literature above. The performance indicators found in the literature are presented in *Table 3:1* below.

Table 3:1. Common Performance Indicators used in Traffic and Public Transport Evaluation.

Category	**Indicator**	**Definition/Purpose**	**Typical Use in Literature**
Travel Time	Mean Travel Time	Average observed travel time along a route or corridor	Measures overall efficiency (Berkow et al., 2009; Arhin et al., 2022)
	Median Travel Time	Central value of travel time distribution	Represents typical conditions (Büchel & Corman, 2020)
	Percentile Travel Time	Upper bound of travel time distribution	Captures extreme delays (Berkow et al., 2009; Büchel & Corman, 2020)
	Travel Time Standard Deviation	Dispersion of travel times	Measures variability (Bajić et al., 2022)
Speed	Operation Speed	Distance divided by travel time	Indicates efficiency (Arhin et al., 2022)
	Mean/Median Speed	Average or typical speed	Assesses corridor performance (Berkow et al., 2009)
Headway	Mean Headway	Average time between vehicles	Represents service frequency (Strathman & Kimpel, 2003)
	Headway Standard Deviation	Variation between vehicles	Captures irregular service (Bajić et al., 2022)
	Coefficient of Variation	Standardised variability measure	Key reliability indicator (Strathman & Kimpel, 2003; Bajić et al., 2022)
Reliability	Travel Time Reliability	Consistency of travel time	Affects passenger perception (Soza-Parra et al., 2022)

	On-time Performance	Adherence to schedule	Used in schedule-based systems (Liu et al., 2023)
Variability	Percentile-based Robustness	Upper percentile metrics	Assess congestion performance (Büchel & Corman, 2020)
Passenger	Waiting Time	Time passengers wait	Derived from headways (Strathman & Kimpel, 2003)
	Excess Waiting Time	Additional wait due to irregularity	Reflects perceived reliability (Ansari Esfeh et al., 2020)
Corridor	Travel Time Savings	Before-and-after travel time difference	Evaluates interventions (Aemmer et al., 2022)
	Change in Speed	Speed variation over time	Measures efficiency improvements (Aemmer et al., 2022)
	Change in Variability	Change in dispersion	Indicates reliability changes (Liu et al., 2023)

Table 3:1 summarises indicators from previous research, consistently highlighting travel time and speed-based measures as the primary indicators for evaluating high-frequency public transport systems. Notably, percentile-based travel time metrics are recognised as essential for capturing reliability and robustness in real-world operating conditions.

A synthesis of the reviewed indicators shows that measures of travel time, operating speed, and variability are most relevant for evaluating operational effects in high-frequency bus services. These indicators capture both central tendencies and dispersion, allowing the analysis to reflect typical performance and sensitivity to congestion and disturbances. This is particularly important because dedicated bus lanes and variability are central to the analysis.

Due to the limited time for this study, only a few indicators were selected. Based on the review from *Table 3:1* indicators that align with established practice could be selected. Two categories were selected, *Travel Time* and *Speed*, along with the connected indicators.

3.5 Data Quality Assurance

Reliable conclusions about the effects of bus lanes require high-quality data. Because indicators like variability and travel time reliability are

sensitive to missing or erroneous records, data quality assurance is central to this thesis's analysis.

High-frequency AVL and GTFS data are especially vulnerable to quality issues, which can distort the indicators central to this thesis (Batini et al., 2009; Aemmer et al., 2022; Liu et al., 2023; Hrubeš et al., 2024). These quality assurance steps are designed to protect against such biases and ensure the indicators reflect real operational effects.

The goal is to ensure indicators accurately capture operational changes – especially when comparing before and after bus lane implementation or across routes (Batini et al., 2009; Liu et al., 2023; Hrubeš et al., 2024).

Reliable analysis of public transport performance depends on high-quality data. Issues like missing stop events, duplicate records, or inconsistent timestamps can distort key indicators, including travel time and reliability. As Hrubeš et al. (2024) note, ensuring data quality must be integrated throughout the analytical process, especially as datasets grow larger and more complex. Embedding quality assurance at every stage helps ensure findings reflect real-world conditions rather than data artefacts. This perspective, highlighted by Hrubeš et al. (2024) and recent work on anomaly detection and data governance (Purkrábková et al., 2024; 2025), is now widely recognised.

Data quality is especially important for high-frequency services, where minor timing errors can create the illusion of bus bunching, delays, or improvements that are just artefacts. Rigorous quality checks help prevent mistaken conclusions about performance. The field increasingly relies on advanced anomaly detection methods. Purkrábková et al. (2024, 2025) describe automated tools to detect and correct such errors, making performance analysis more reliable and transparent.

Recent reviews underscore the need for structured data governance as both data volume and complexity grow (Hrubeš et al., 2024). Data governance involves shared processes, policies, and standards to keep data high-quality, secure, and useful. Successful governance in transport requires both technological solutions and organisational commitment to adapt to challenges like data integration and standardisation. Blending top-down and bottom-up approaches (explained further later) helps organisations stay agile while maintaining reliability and transparency. Purkrábková et al. (2024, 2025) demonstrate how advanced statistical techniques – such as Generalised Additive Models (GAM)– support traffic data management

and anomaly detection. By flagging irregularities and supporting reproducible workflows, these tools help evaluate data quality. Across these studies, methodological rigour and the adoption of both classical and innovative tools are emphasised to meet the demands of modern transport systems.

Recent developments show the value of advanced statistical methods for data quality control and anomaly detection. Purkrábková et al. (2024) demonstrate how GAMs help identify anomalies in large traffic datasets, strengthening data governance with automated tools. Incorporating these best practices is especially relevant in studies like this, where robust, transparent data management underpins credible performance evaluation. Other studies highlight the importance of standardisation, metadata consistency, and reproducible workflows for maintaining data quality over time (Batini et al., 2009; Peng, 2011; Liu et al., 2023).

To manage data quality, researchers use structured frameworks to check, filter, and validate data before analysis. As Hrubeš et al. (2024) review, there are two main approaches: top-down, with requirements set in advance, and bottom-up, where rules are developed after the data. In a top-down approach, quality standards – such as completeness or consistency – are set at the start and then applied throughout the dataset. This keeps things consistent, but it can be less flexible for complex or multi-source data. Bottom-up approaches start with exploring the data – looking for patterns and outliers – before setting quality standards. This lets researchers tailor rules to each dataset, which is valuable for large, continuously gathered transport data. Recent work shows that combining bottom-up and top-down approaches with flexible statistical modelling improves anomaly detection and data quality. Literature consensus is that combining these strategies yields the most reliable results (Hrubeš et al., 2024).

To assess data quality, researchers consider several key dimensions:

Completeness	Is all expected data present?
Consistency	Are rules and formats followed?
Validity	Are values reasonable?
Timeliness	Is data up to date?
Accuracy	Do records reflect reality?

These dimensions, widely used in transport research (Batini et al., 2009; Hrubeš et al., 2024), help researchers identify weaknesses and decide what to trust for analysis.

3.6 Summary & Positioning of Thesis

The literature consistently finds that dedicated bus lanes improve travel time and reliability, especially in congested corridors (Arhin et al., 2022; Keolis Sverige, 2020; El-Geneidy et al., 2006). These factors are central to how passengers assess and choose public transport (Soza-Parra et al., 2022). Building on this foundation, this thesis evaluates the Örebro bus lanes using travel time and speed (the indicators most widely adopted for high-frequency bus services) (Berkow et al., 2009; Büchel & Corman, 2020; Arhin et al., 2022).

At the same time, this thesis adopts a narrower focus than some previous studies. Rather than combining AVL with schedule-linked GTFS-RT data to compare observed and scheduled performance, it uses only AVL/`VehiclePositions` data and turns to static GTFS solely for route geometry. This trade-off prioritises a direct, observation-based assessment of corridor performance before and after implementation, consistent with headway- and travel-time-based methods that do not require timetable data (Strathman & Kimpel, 2003; Bajić et al., 2022).

The literature on data quality assurance highlights the need for rigorous validation, as metrics like travel time variability are sensitive to missing, duplicated, or misaligned records (Batini et al., 2009; Hrubeš et al., 2024; Liu et al., 023). Thus, the credibility of this thesis depends as much on the quality checks applied to AVL data (*Section 5.2.1*) as on indicator selection. This thesis adopts a blended approach to data quality assurance, as discussed in Section 3.5: certain checks were defined in advance, following a top-down logic, while others were refined based on patterns identified during exploratory inspection of the data, reflecting a bottom-up element. In line with the field's consensus that robust data governance is essential for reliable evaluation (Hrubeš et al., 2024; Purkrábková et al., 2024, 2025), this study presents a before-and-after analysis of Örebro's bus lanes as a case study applying these principles to a Swedish mid-sized city (a context less explored than major metropolitan areas).

4 THEORETICAL FRAMEWORK

This section establishes the theoretical foundation for analysing how dedicated bus lanes influence urban bus operations. It introduces the key concepts and analytical tools that guide the selection of performance indicators in this study, focusing on high-frequency, road-based bus services in dense urban environments.

Public transport systems are networks of events (bus movements, arrivals, and departures) occurring at specific places and times (Strathman & Kimpel, 2003; Büchel & Corman, 2020). The sequence and variability of these events, not just strict timetables, shape the experience for operators and passengers. This perspective motivates using operational data to evaluate performance.

4.1 PERFORMANCE DIMENSIONS

Evaluating public transport performance requires a multidimensional approach, since infrastructure interventions rarely affect only one aspect of the service. In urban networks, system behaviour emerges from interactions among buses, traffic, and road design.

Four core performance dimensions are considered:

- *Operational efficiency,* minimising travel time and maximising operating speed
- *Reliability,* consistency of service delivery over time
- *Variability,* fluctuations in performance between trips
- *Robustness,* ability to maintain stable performance under varying conditions

These dimensions are interconnected but capture distinct aspects of system behaviour. Efficiency reflects average conditions; reliability and variability describe predictability; and robustness reflects concerns about performance under stress (Bajić et al., 2022; Büchel & Corman, 2020). Dedicated bus lanes primarily aim to reduce disruptions and unpredictable delays, making these dimensions especially relevant.

These dimensions are operationalised in this thesis through two indicators: travel time and operating speed, defined formally with their governing equations in *Section 4.3*. *Section 4.4* summarises both indicators using the

descriptive statistics introduced there, and *Section 4.2* describes their empirical distributions (including the percentile-based measures used to describe skew and extreme values). *Sections 4.4* and *4.6* describe the tools used to compute and visualise these indicators, including the relational database and geographic information system underpinning the analysis.

4.2 Variability & Robustness

Rather than assuming travel times or speeds follow a known theoretical distribution (such as the normal distribution), this thesis works directly with the empirical distribution of observed values (that is, the actual frequency with which different values occur in the collected data). This approach is appropriate because travel time and speed distributions in urban traffic are frequently skewed, with a cluster of typical values and a longer tail of occasional severe delays, rather than being symmetric. A percentile (P_k) describes the value below which a given proportion *k* of observations falls (the 95th percentile (P_{95}) of travel time, for example, is the value below which 95% of observed trips fall, and therefore represents a threshold exceeded only by the slowest 5% of trips). *Figure 4:1* illustrates this hypothetical skewed travel time distribution, showing the median (P_{50}) and 5th (P_{05})/95th (P_{95}) percentiles across the full spread of observations.

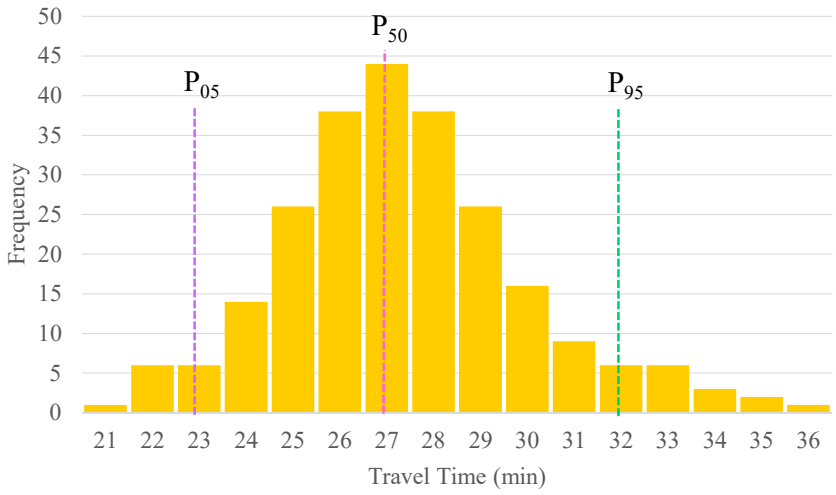


Figure 4:1. Illustrative Histogram of a Hypothetical Travel Time Distribution, showing 5th percentile (P_{05}), Median (P_{50}), and 95th percentile (P_{95}).

Variability describes how much key performance indicators differ across repeated observations. Even if the average travel time is acceptable, large fluctuations can make the service feel unreliable. To quantify this, transport studies commonly use statistical measures of dispersion, including variance and standard deviation (Büchel & Corman, 2020; Ansari Esfeh et al., 2022).

Variance captures how far individual observations deviate from the mean on average, reflecting the average squared distance between data points and the mean. *Standard deviation*, the square root of the variance, expresses this spread in the original unit of measurement, making it easier to interpret and apply in real-world contexts. Higher variability indicates unpredictable waiting times or travel durations, while lower variability suggests a stable and dependable service. These measures are essential for evaluating how infrastructure interventions affect day-to-day operations and the overall operational quality of public transport systems (Bajić et al., 2022; Büchel & Corman, 2020).

Passengers are sensitive not only to average travel and waiting times but also to their consistency and predictability (Büchel & Corman, 2020; Ansari Esfeh et al., 2022). In transport studies, variance and standard deviation are frequently used to capture changes in travel time, providing clear insights into service stability and reliability.

Robustness extends variability by focusing on system behaviour under adverse conditions, such as peak-hour congestion or disruptions. It reflects the system's ability to maintain acceptable performance levels despite external pressures. To capture both variability and robustness, transport studies often use percentile-based indicators (e.g., the 95^{th} percentile travel time (P_{95})) alongside mean values. These percentiles represent the upper bound of observed delays and reflect the worst conditions passengers experience. Improvements in these measures indicate increased resilience and reduced exposure to extreme delays (Bajić et al., 2022; Büchel & Corman, 2020).

Infrastructure measures that reduce interaction with mixed traffic, such as dedicated bus lanes and signal prioritisation, are expected to reduce both variability and extreme delays, thereby improving overall robustness (Bajić et al., 2022; Büchel & Corman, 2020).

Another important consideration for robustness and reliability is scheduled buffer (or recovery) time (the extra time built into timetables at certain

stops to allow buses that arrive early to wait for their scheduled departure). This common timetable strategy helps absorb minor delays and keeps bus headways regular. In this thesis, however, it was not possible to distinguish scheduled buffer time from ordinary passenger dwell time or unplanned delays. The AVL data do not include scheduled dwell information, and the static GTFS data for the corridor lacked sufficiently detailed arrival and departure times to separate buffer times. Consequently, some of the recorded travel and dwell times may reflect planned schedule adherence rather than actual operational conditions, which should be considered when interpreting the travel time and reliability results discussed in this thesis.

4.2.1 STATISTICAL SIGNIFICANCE TESTING

Travel time and speed data are often not normally distributed but instead exhibit a noticeable skew. As a result, using a standard t-test (which assumes normally distributed data) can lead to misleading conclusions when comparing two periods. To address this, this thesis applies the Mann-Whitney U test (Mann & Whitney, 1947), a nonparametric approach that determines whether one distribution tends to produce higher or lower values than another by ranking all observations from both periods together, rather than focusing solely on their means. This method is particularly appropriate for the skewed, real-world data encountered in travel time and speed analyses, and it ensures that the significance test is consistent with using the median as a measure of typical performance (see *Section 4.4*).

A practical challenge arises when two or more observations have the same values (referred to as tied observations). When ties occur, it is not possible to assign each observation a unique rank. Instead, each tied value receives the average of the ranks it would otherwise occupy (e.g., two observations tied for 5th and 6th place would both receive rank 5.5). Without this adjustment, the test tends to overestimate the variance, increasing the likelihood of finding a significant result even when the data do not support it. To address this, the standard correction modifies the variance used in the test as follows:

Equation 4:1. Variance of U with Tie Correction.

$$\sigma_u^2 = \left(\frac{n_1 n_2}{12}\right) \times ((N+1) - \sum \frac{t^3 - t}{N(N-1)}$$

Where n_1 and n_2 are the sample sizes for the two groups being compared, $N = n_1 + n_2$, and t is the number of observations sharing each tied value,

summed across all distinct tied groups (Hollander, Wolfe & Chicken, 2014).

4.3 TRAVEL TIME & OPERATIONAL SPEED

Travel time and operating speed are fundamental indicators of public transport efficiency. Travel time is derived from observed timestamps of vehicle movements, while operating speed is calculated as a distance divided by travel time (Berkow et al., 2009; Arhin et al., 2022).

For each trip (i) along the study area, the travel time can be expressed as:

Equation 4:2. Travel Time.

$$T_i = t_{end,i} - t_{start,i}$$

Here, $t_{start,i}$ and $t_{end,i}$, represent the timestamps of the first and the last observed positions matched to the study area for that trip. The operating speed is then calculated by dividing the distance by the travel time:

Equation 4:3. Operating Speed.

$$v_i = \frac{d_i}{T_i}$$

Where d_i is the distance covered along the study area. Since each trip can be affected by different factors, travel time and speed are not fixed values. Instead, they are represented as empirical distributions based on many observed trips. Consistent with the approach in *Section 4.2*, the median characterises typical performance, while percentiles and standard deviation describe variability.

4.4 DESCRIPTIVE STATISTICS

Throughout this thesis, the median summarises travel time and operating speed observations, as it provides insight into typical performance.

The median is the middle value of a set of observations sorted in ascending order. Because the median depends on the position of values in sorted order (not their magnitude), a handful of extreme values has little impact. For this reason, the median is often a more representative measure of typical performance, especially when the underlying distribution is skewed

(Berkow et al., 2009; Büchel & Corman, 2020), as is expected for travel time and speed in this thesis (*Section 4.2*). Consequently, the median is used as the primary statistic for comparing performance between 2023 and 2025 in *Section 6*.

Beyond central tendency, the variability of observations around the median is also important when evaluating performance. A low median travel time only signifies improvement if it is not accompanied by high variability. *Section 4.2* defines and discusses measures such as standard deviation and percentile-based ranges.

4.5 Relational Databases

The AVL dataset used in this thesis contains over 125 million position records across two study periods (*Section 2.3*), necessitating a data model that can effectively store, filter, and join large tabular datasets. A relational database organises this information into structured tables linked by shared keys, so details like vehicle positions, route geometries, and derived indicators remain distinct but easily connected through queries (Elmasri & Navathe, 2016). Expressing the data processing pipeline as a series of structured queries, rather than improvised scripts, makes each step explicit and auditable and ensures reproducibility: running the same queries on the same raw data will always yield the same results (Peng, 2011). *Section 5.2* describes the specific database system used.

4.6 Data Quality in Performance Evaluation

Robust performance evaluation depends on high-quality data. Metrics like travel time and operating speed are particularly sensitive to missing, inconsistent, or implausible observations (Batini et al., 2009; Liu et al., 2023).

Data quality frameworks for transit typically distinguish between schedule-centric data (records tied to scheduled trips and timetables) and physical-centric data, which are raw, timestamped vehicle positions with no schedule reference (see *Section 5.2.1*). Because this thesis uses only physical-centric AVL data, the analysis is not tied to a specific schedule, and comparing adherence to schedules would mix true performance changes with changes in service expectations. By focusing on observed vehicle movement, this analysis avoids that issue.

This thesis assesses the quality of the physical-centric dataset using three dimensions, adapted from established frameworks (Batini et al., 2009; Hrubeš et al., 2024), and translates them for AVL position records:

COMPLETENESS

Most transit-data frameworks define completeness in terms of missing stops, events, or scheduled trips, checks that require schedule-linked data, which this thesis does not use. Still, missing timestamps, incomplete trajectories, or missing records are common in real-time feeds (Webb et al., 2025) and can disrupt vehicle movement reconstruction, especially in high-frequency systems (Aemmer et al., 2022; Liu et al., 2023). For AVL data, completeness means each record must include a vehicle identifier, coordinate pair, and timestamp. Records missing any of these are unusable. This is assessed in *Section 5.2.1*.

CONSISTENCY

Consistency checks whether data follows logical temporal and structural patterns. Integration errors or delays can create inconsistencies that distort performance metrics (Webb et al., 2025; Aemmer et al., 2022). While typical frameworks might check alignment with scheduled routes, that is not relevant here. Instead, this thesis checks if each vehicle's recorded positions are internally consistent: timestamps must move forward in time, and no vehicle should have more than one position at the same instant. Any violations would corrupt travel time calculations (*Section 5.3.1*). *Section 5.2.1* describes these checks.

VALIDITY

Validity considers whether the data makes sense in the real world. Implausible speeds, impossible locations, and inconsistent timestamps often point to sensor or system errors. While minor problems may not matter in large datasets, systematic validity issues can bias results (Batini et al., 2009; Hrubeš et al., 2024; Liu et al., 2023). For AVL data, this thesis assesses two aspects: geographic validity (whether coordinates are plausible for the study area; *Section 5.2.1*) and movement realism (whether the speed between consecutive positions is feasible for an urban bus; *Section 5.2.1*). Both aim to catch GPS errors, but at different scales: geographic validity finds major positioning failures, while movement realism detects subtler errors that result in impossible trajectories.

Together, these three dimensions determine if the physical-centric dataset is "fit for use" (Batini et al., 2009; Hrubeš et al., 2024) for the travel time and speed calculations.

5 STUDY DESIGN

This section details the procedures undertaken to evaluate the operational effects of dedicated bus lanes in Örebro. The following sections explain how data were collected, processed, quality-assured, and analysed, as well as the methodologies used to capture performance indicators.

The study adopts a quantitative, observational before-and-after design, leveraging historical public transport data. It examines changes in travel times, speed, reliability, and variability observed after the introduction of dedicated bus lanes. These focal points are chosen for their direct relevance to passenger experience and operational efficiency.

The sub-sections in this Section will be divided according to the steps in *Figure 1:1. Flowchart of the thesis method.*

5.1 DATA COLLECTION & PREPARATION

The volume and structure of the AVL data used in this thesis, over 125 million individual position records across the two study periods (*Section 2.3*), required a system that could efficiently store, filter, and join large tabular datasets. A relational database (PostgreSQL, with the PostGIS spatial extension) was used for this purpose. Structuring the data relationally lets vehicle positions, route geometries, and derived indicators appear as separate but linkable tables and lets the entire processing pipeline (from raw position data through cleaning, spatial matching, and indicator calculation) be expressed as a sequence of SQL queries. This has two practical benefits for this thesis: it makes each processing step explicit and auditable, and it makes the full pipeline reproducible, since rerunning the same queries against the same raw data always produces the same result.

5.1.1 DATA COLLECTION

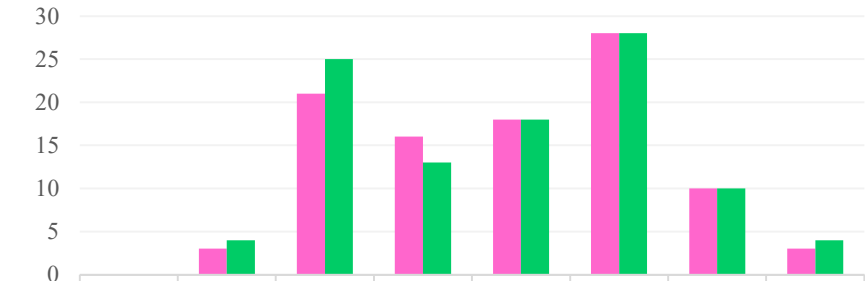
The analysis uses data retrieved from KoDa, which provides access to public transport datasets from Trafiklab, a historical open-data archive developed by RISE and Vinnova in cooperation with Trafiklab, which stores historic GTFS static and GTFS-Realtime data collected from Swedish public transport authorities since February 2020 (Trafiklab, 2026b). Data for this thesis were retrieved via the KoDa API (Trafiklab,

2026b), using the operator code `orebro` for the two study periods: 2-8 October 2023 and 6-12 October 2025. Two data sources are used:

- GTFS static: describes planned services, including routes, stops, and timetables, retrieved from the KoDa static endpoint (`https://api.koda.trafiklab.se/KoDa/api/v2/gtfs-rt/orebro/VehiclePositions?date={date}&key={api_key}`). In this thesis, only route geometries are used to define the corridor and assign observations to bus lines; stop and timetable information is not used.
- GTFS-Realtime (GTFS-RT), `VehiclePositions` feed: provides observed vehicle positions, timestamps, and vehicle identification. This data forms the empirical basis for this thesis and is retrieved from the KoDa real-time endpoint (`https://api.koda.trafiklab.se/KoDa/api/v2/gtfs-static/orebro?date={date}&key={api_key}`). The GTFS-RT TripUpdates feed, which reports schedule-linked arrival and departure predictions, is not used. The real-time data originates from onboard vehicle systems and is stored in their original format without prior correction.

5.1.2 TEMPORAL SCOPE

The evaluation compares operational performance before and after implementing dedicated bus lanes, drawing exclusively on observations of actual bus operations rather than simulation or forecasting. This empirical approach is intended to ensure that the findings are grounded in real-world outcomes.



	00:00-02:59	03:00-05:59	06:00-08:59	09:00-11:59	12:00-14:59	15:00-17:59	18:00-20:59	21:00-23:59
Cars	0	3	21	16	18	28	10	3
PT	0	4	25	13	18	28	10	4

Figure 5:1. Time of Day for Car Travel in 2022 (Svensk Kollektivtrafik, 2022).

Figure 5:1 illustrates the distribution of journeys by time of day for both car travel and public transport. The figure highlights the concentration of trips during the morning and afternoon, which correspond to commuting times. These peaks justify the analysis periods selected in this study, as they represent conditions in which congestion and variability are most pronounced and bus priority measures are expected to have the greatest impact.

To capture variation in traffic conditions, the analysis is conducted for three time periods:

Morning peak:	06:00 – 08:59
Afternoon peak:	15:00 – 17:59
Night:	18:00 – 23:59

The analysis focuses on a specific week for data collection: the first week of October in both 2023 and 2025. This was selected based on two key constraints: data collection began in September 2023; however, construction of the BRT-inspired measures for the selected sections began in Örebro in February 2024 and opened again in October 2025. This week was chosen to capture representative conditions while adhering to these practical limitations; it was also a month without holidays and no winter conditions. Data from all seven days of each study week were pooled together without distinguishing weekdays from weekends.

5.1.3 STUDY AREA

The analysis focuses on Sections 7-9 of the BRT corridor in Örebro (see *Figure 2:3* and *Figure 2:4* in *Section 2.2.1*), where dedicated bus lanes and signal prioritisation have been implemented to enhance service quality and passenger experience.

For both the before- and after-analysis, bus lines are classified according to their level of exposure to the BRT corridor:

Trunk lines: refer to services that operate continuously along the studied corridor section, representing full exposure to the intervention.

Small Trunk lines: denote services that traverse only a portion of the corridor within the study area, thereby exhibiting partial exposure.

The specific bus lines chosen for this thesis and their classification are listed below in *Table 5:1*.

Table 5:1. Included bus lines in the analysis and their classification.

Year	Trunk Lines	Small Trunk Lines
2023	1, 2	6, 9
2025	1, 2	5, 7

The selection of bus lines is based on the official route structure and service design of the Örebro public transport network (Region Örebro, 2025; Länstrafiken Örebro, 2025). Below in *Figure 5:2* are the Trunk Services lines for the two years drawn together with the study area.

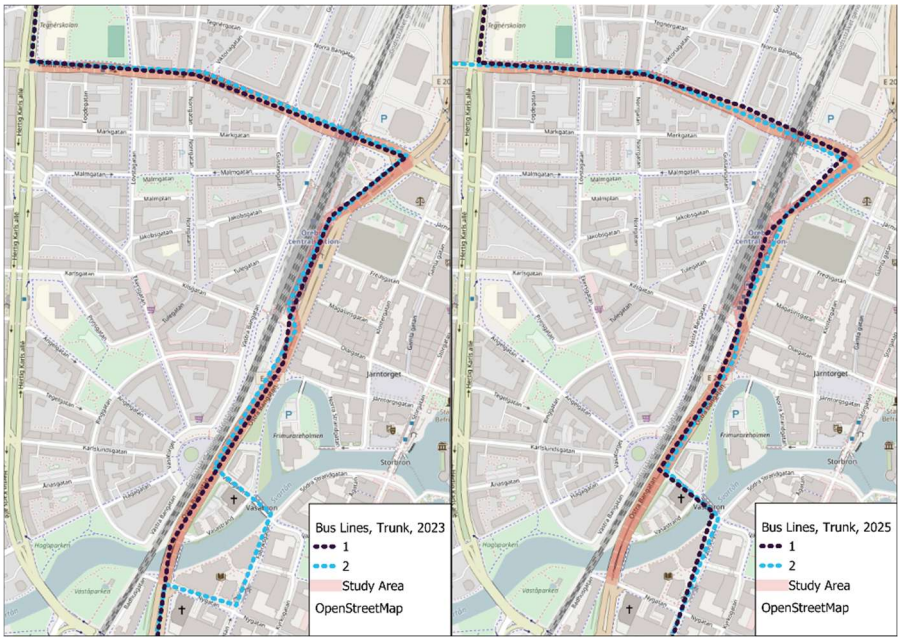


Figure 5:2. Selected Trunk Service bus lines in the study area.

Figure 5:3 shows the small trunk service lines drawn together with the study area.

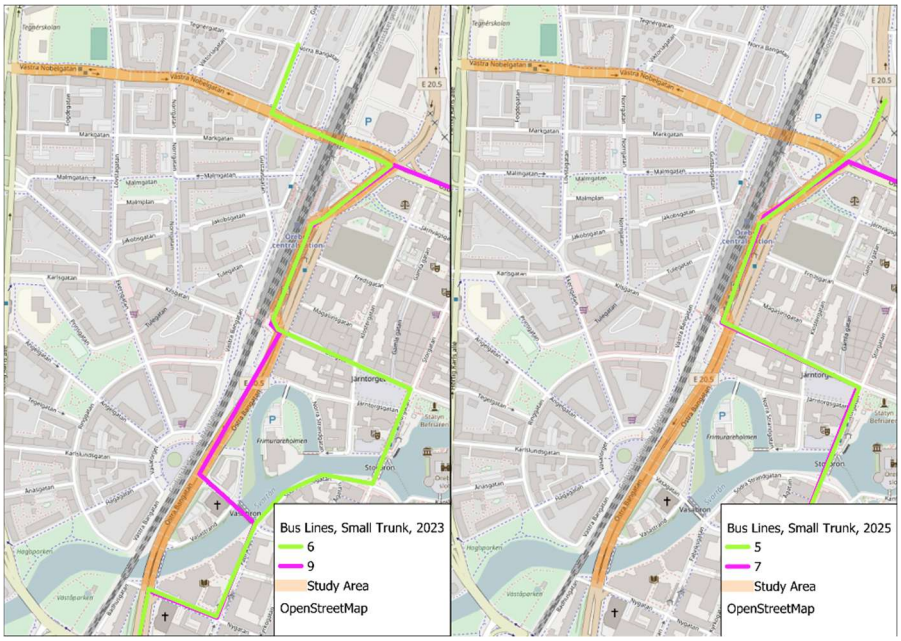


Figure 5:3. Selected Small Trunk service bus lines in the study area.

This classification enables a nuanced comparison between services with different degrees of exposure to the intervention, supporting a more comprehensive understanding of the operational effects.

5.2 Data Processing

Raw AVL position records are transformed into a structured dataset of corridor-level movements through four steps, each described in full in the sections that follow:

- Deduplication (*Section 5.3.1*): because the AVL feed reports a vehicle's position repeatedly while stationary, records are reduced to one observation per vehicle per minute before any distance or speed calculation.
- Data quality assurance (*Section 5.2.1*): the deduplicated records are validated for completeness, geographic validity, temporal consistency, movement realism, and vehicle identity consistency, corresponding to the data quality dimensions.

- Spatial matching (*Section 5.2.2*): each validated position is located along the corridor using linear referencing against a single centreline and assigned to a 25-metre grid cell based on that position.
- Indicator calculation (*Section 5.3.1*): travel time and operating speed are calculated from the matched, grid-referenced observations.

All processing is carried out using SQL-based queries on the relational database described in *Section 4.5*, making each step explicit and reproducible.

5.2.1 DATA QUALITY ASSURANCE

Real-time public transport data generally falls into two broad categories, each defined by its underlying structure and generation method. *Schedule-centric* data comprises records linked to a specific trip identification number, capturing stop-by-stop predictions, delays, and arrival or departure times in relation to a planned timetable (such as GTFS static data). These records can exist before a vehicle begins its journey, predict future events, and update as new information becomes available. In contrast, *physical-centric* data consists of vehicle position records, each associated with a vehicle identification number and reporting latitude, longitude, and timestamp; some feeds also include bearing, speed, or an optional trip reference. This data type provides a real-time snapshot of a vehicle's actual location, updated frequently (often every few seconds), and does not include predictions about future events.

Because these two data types differ substantially in structure, update behaviour, and the failure modes they are susceptible to, data quality assurance must generally be performed separately for each. This thesis's empirical analysis relies solely on the physical-centric dataset (vehicle position records, delivered via the GTFS-RT VehiclePositions feed described in *Section 5.1.1*); no schedule-centric data (GTFS-RT `TripUpdates`) is used, and consequently no schedule-centric quality assurance was performed. This section documents the validation procedure applied to the physical-centric AVL (Automatic Vehicle Location) data.

RATIONALE & OVERVIEW

Physical-centric data faces distinct data quality risks compared to schedule-centric data. These risks stem from its nature as a continuous, high-frequency stream of real-time observations, rather than as discrete, predictive updates anchored to a fixed timetable. To address these challenges, five categories of validation were implemented: completeness, geographic validity, temporal consistency, movement realism, and vehicle identity consistency. The first category serves as a fundamental structural check, while the remaining four align with the core characteristics of physical-centric data described above.

All validation procedures were implemented in SQL, using the raw vehicle-position table (`vehicle_position_all`) as the primary data source. Each identified issue was recorded in a dedicated results table (`vehicle_validation_results`), which captured the error category, relevant vehicle and trip identifiers, the record's timestamp, and a human-readable description. This approach enabled independent assessment of each validation dimension, while also maintaining a comprehensive record of all detected issues. Summary statistics could then be derived from this unified dataset.

To assess the consistency between consecutive records, the raw position table was first enhanced by including the preceding observation for each vehicle. This was accomplished using a window function (`LAG`) partitioned by vehicle identifier and ordered by timestamp, providing, for each record, the timestamp and coordinates of that vehicle's immediately previous position, without the need for a self-join. The resulting enriched table (`vehicle_enriched`) served as the foundation for temporal consistency and movement realism checks described in the following sections.

COMPLETENESS

The first validation dimension checked whether each record contains values for the three fields needed for subsequent analysis: vehicle identifier, coordinate pair (latitude and longitude), and timestamp. These fields are essential structural components, not optional metadata. Without a vehicle identifier, a record cannot be attributed to a specific vehicle's trajectory; without coordinates, it cannot be evaluated for geographic validity or used in spatial joins; and without a timestamp, it cannot be chronologically ordered, which is critical for temporal and movement checks. Consequently, any AVL message missing one or more of these fields is not

simply of low quality but is rendered unusable for all substantive checks that follow. Identify and quantify these records separately before further validation.

Three separate conditions were assessed: `vehicle_id IS NULL`, `latitude IS NULL or longitude IS NULL`, and `timestamp IS NULL`. Each was logged under its own error category (`MISSING_VEHICLE_ID`, `MISSING_POSITION`, and `MISSING_TIMESTAMP`, respectively) instead of being grouped into a single "incomplete record" classification. This approach allows reporting the relative frequency of each specific failure mode individually. These records were retained in the summary rather than discarded before validation, so their frequency could indicate upstream feed quality.

GEOGRAPHIC VALIDITY

The second validation dimension evaluates whether a record's coordinates fall within a plausible bounding region for the study area. GPS receivers on transit vehicles can, for various reasons (such as receiver faults, signal multipath in dense urban environments, or message corruption), report positions that place a vehicle well outside its true operating area. These errors may include invalid or degenerate values like (0,0) (commonly referred to as "null island"), transposed coordinate orders, or false readings resulting from receiver initialisation before acquiring a valid satellite fix. If left uncorrected, such records can compromise any spatial analysis based on this data, e.g., the map-matching procedure used elsewhere in this thesis to assign vehicle positions to route segments, which relies on coordinates being at least approximately correct.

Records with non-null coordinates that fell outside a broadly defined latitude and longitude envelope were flagged as `INVALID_COORDINATES`. This envelope was intentionally set to encompass the operational area with a significant margin, ensuring the check identified only major positioning failures rather than evaluating fine-grained positional accuracy. Minor GPS measurement errors of a few metres are expected and addressed by the spatial matching tolerance in the travel time analysis, rather than by this validation step.

TEMPORAL CONSISTENCY

The third validation dimension addresses two related but distinct issues: first, ensuring that timestamps for a given vehicle increase strictly across its

sequence of recorded positions; and second, confirming that no vehicle has more than one position record at the same timestamp. Both requirements reflect fundamental expectations for a well-formed real-time position feed. A backward step in time (where a record's timestamp precedes that of the previous record for the same vehicle) is not physically plausible and signals a feed issue, such as message reordering during transmission, clock drift or resynchronisation on the vehicle's onboard unit, or data corruption. Because the travel time methodology developed in this thesis relies on processing each vehicle's positions in chronological order to calculate elapsed times, any such inversion, if uncorrected, could produce inaccurate (including negative) travel time values in downstream analyses. Duplicate timestamps present a similar risk: a reliable feed should report only one position per vehicle at any given instant. Repeated records at the same timestamp (especially when they contain conflicting positions) may indicate a transmission fault or a downstream ingestion error, risking double-counting a single observation.

Backward movement was identified by comparing each record's timestamp with that of the immediately preceding record for the same vehicle, as provided by the enriched table described earlier. Any instance in which the current timestamp was earlier than the previous one was flagged as `TIME_BACKWARDS`. Duplication was detected by grouping records by vehicle, trip, and timestamp, and flagging any group that contained more than one record as `DUPLICATE_POSITION`.

MOVEMENT REALISM

The fourth validation dimension examines whether the speed implied by two consecutive positions for the same vehicle is physically plausible for an urban bus. GPS positioning errors (caused by multipath reflections, temporary loss and reacquisition of satellite signals, or receiver malfunctions) can yield position readings that are significantly displaced from a vehicle's true location, even though the recorded timestamp remains accurate. Such erroneous positions are inconsistent with the vehicle's actual trajectory and often imply unrealistic speeds relative to adjacent records. This check used implied speed (distance divided by elapsed time) rather than distance alone, since the two are not equivalent. A large change in position between two records may be reasonable if the interval between them is long (e.g., after a reporting gap) but is implausible if the same distance is covered in just a few seconds. Assessing displacement without

considering elapsed time could both miss genuine short-interval errors and mistakenly flag legitimate long-interval movements as problematic.

For each pair of consecutive records for a given vehicle, the Euclidean distance between the two sets of coordinates was calculated and divided by the elapsed time between their timestamps, yielding an implied speed. If this implied speed exceeded a predefined threshold (determined based on the maximum speed realistically achievable by a bus within the study area's urban road network), the record was flagged as `UNREALISTIC_MOVEMENT`.

VEHICLE IDENTITY CONSISTENCY

The fifth validation dimension addresses whether a single vehicle identifier is associated with more than one distinct trip identifier at the same timestamp. Since a physical vehicle can operate only one trip at any given time, simultaneous association with multiple trip identifiers is logically impossible and indicates inconsistencies in how the AVL feed assigns trips to vehicles. This may occur, for instance, during routine operational vehicle reassignments that are not immediately or cleanly reflected in the data stream, resulting in a brief overlap where both outgoing and incoming trip assignments appear simultaneously. If left unchecked, such records can attribute a single vehicle's position to two trips at once, compromising downstream trip-level analyses.

To detect this issue, records were grouped by vehicle identifier and timestamp. Any group associated with more than one distinct trip identifier was flagged as `MULTIPLE_TRIPS_PER_VEHICLE`.

SUMMARY STATISTICS

The individual validation results were then aggregated into a summary table, reporting for each error category the total number of affected records and the proportion of the overall dataset this represents. Because a single record can be flagged under multiple categories simultaneously (e.g., both a missing timestamp and an out-of-region coordinate), these proportions are not mutually exclusive and do not sum to the total dataset size.

5.2.2 SPATIAL ANALYSIS & VISUALISATION

Spatial analysis connects performance indicators directly to their geographic context along the corridor. In this study, indicators such as travel time and speed are summarised at the grid-cell level and visualised

along the corridor centreline. This approach enables the identification of specific locations where bottlenecks or localised delays occur, as well as highlighting variations in performance across different segments.

To facilitate spatial analysis, the study corridor was divided into uniform 25-metre segments, referred to as “grid cells”, using linear referencing along a single continuous centreline. This cell size was selected based on the approximate width of the studied corridor (roughly 20-25 metres). A round, interpretable value was preferred to support clear visual communication of spatial results in the resulting maps (*Figure 6:5Figure 6:10*). Each GPS observation was mapped to a corresponding grid cell by calculating its position in metres from the corridor’s starting point (using the `ST_LineLocatePoint` function in PostGIS) and then assigning it to the grid cell whose distance range included that position. To improve accuracy, observations located more than 12.5 metres perpendicular to the centreline (half the grid-cell width) were excluded, reducing the risk of mistakenly including GPS points from side streets or adjacent infrastructure. Linear referencing was favoured over simple point-in-polygon matching, as it ensures each observation is positioned correctly along the entire corridor length (even in curved sections) rather than relying solely on the geometric boundaries of each grid cell.

For each grid cell, and for every combination of route, year, and timeslot, the mean, median, standard deviation and 5^{th}/95^{th} percentile speeds were calculated from all valid segment-level speed observations assigned to that cell. These statistics were then combined into a single value for each cell, year, and timeslot, weighted by the number of observations from each relevant route. This approach ensured that cells with greater traffic volumes had a proportionally larger influence on the aggregated results. To evaluate changes over time, the difference in mean speed between the 2023 and 2025 periods was calculated for each grid cell, providing a continuous spatial measure of where operating speed improved, declined, or remained unchanged along the corridor.

The resulting grid-cell indicators were visualised in QGIS (QGIS Development Team, 2025), enabling identification and interpretation of spatial patterns along the corridor. This visual approach made it possible to detect clusters of cells with degraded speeds or localised bottlenecks that may not be apparent from route-level or system-wide summary statistics. By retaining each grid cell's geometry throughout the spatial join process,

the corridor was rendered as a continuous, colour-coded line, illustrating both the magnitude and direction of changes in the selected indicators.

To filter the collected data so that calculations were performed only on the selected segments, a line was drawn on the affected streets (see dark pink line in *Figure 5:4* below). To visualise the study area, the centreline was offset 12.5 metres to approximate the width of the road (see light pink area in *Figure 5:4* below).

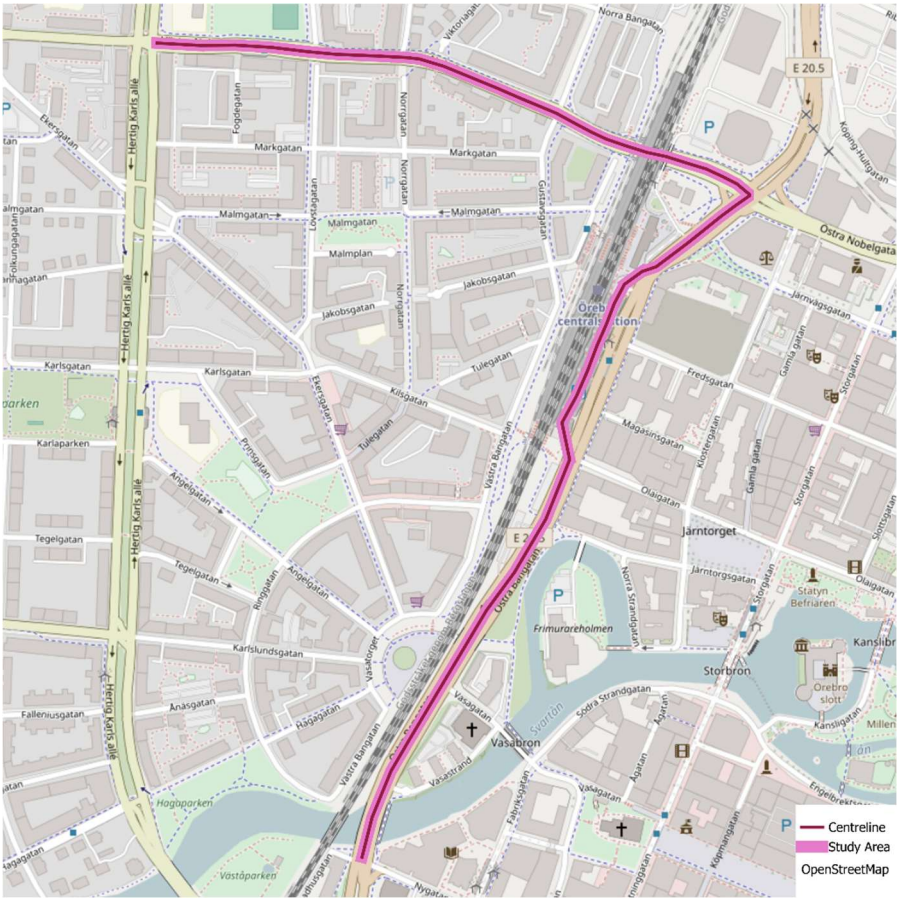


Figure 5:4. Study Area and Centreline.

It is the centreline shown *Figure 5:4* from which the grid cells were created.

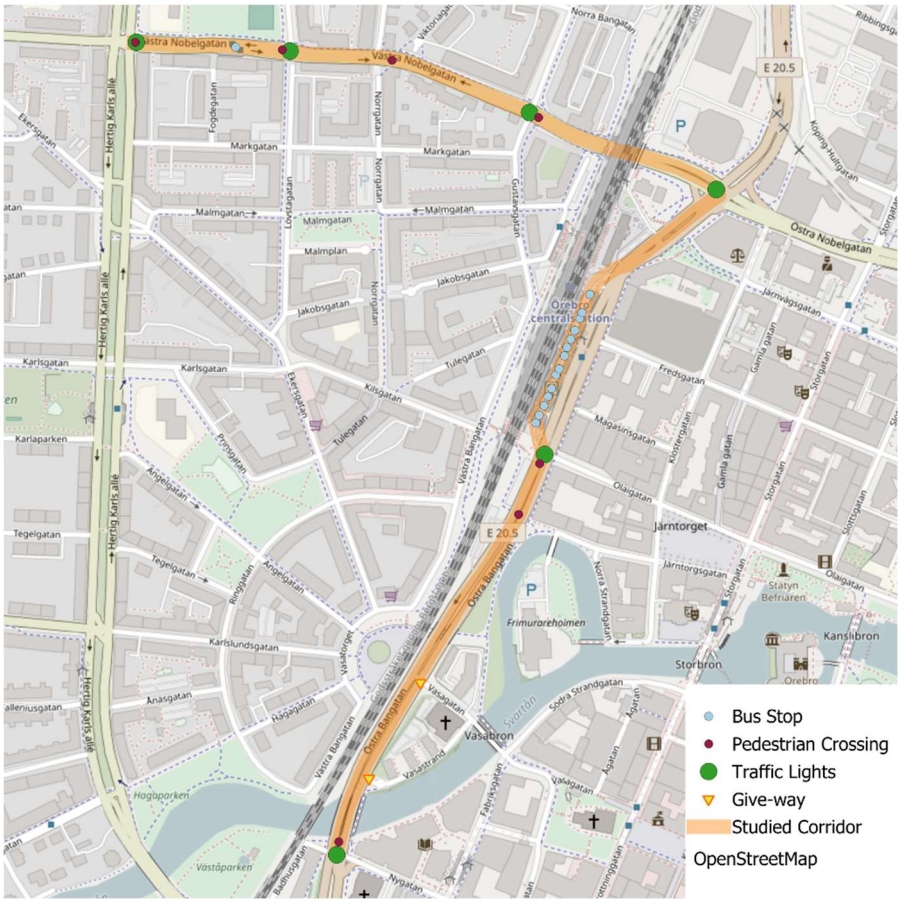


Figure 5:5. Traffic Control Points and Bus Stops along the Studied Corridor.

Figure 5:5 presents the corridor under study, highlighting the locations of traffic signals, pedestrian crossings, give-way signs, and bus stops. These features were mapped through a careful visual review of the OpenStreetMap base map, manually locating and marking each traffic signal, pedestrian crossing, give-way sign, and bus stop along the corridor. To verify the completeness and accuracy of this manual identification, the results were cross-checked against a query of the underlying OpenStreetMap using Overpass Turbo (Raifer, 2026), confirming that manually identified points corresponded to the tagged features (`highway=traffic_signals`, `highway=crossing`, `highway=give_way`, `highway=bus_stop`) within the corridor. The corridor itself extends from Västra Nodelgatan in the northwest, curves

southeast past Örebro central station, and continues along Östra Bangatan toward Rådhusgatan in the south.

Traffic signals are mainly at major intersections; most pedestrian crossings are at these signalised intersections, indicating that most are signal-controlled. The two give-way signs in the southern section, near Vasagatan and Vasastrand, mark unsignalised locations where traffic must yield. A cluster of bus stops near Örebro central station reflects the station's importance as a main interchange along the route.

This arrangement of traffic control points and bus stops matters for the analysis in two main respects. First, both signalised and unsignalised intersections can cause delays unrelated to the bus lane intervention, so their locations help explain differences in travel time across corridor sections (see Research Question 1 in *Section 1.3).* Second, the cluster of bus stops near the central station suggests that dwell time will have a greater impact on overall travel time in that area, which is important when interpreting operational performance by section.

5.3 FINAL OUTPUT

This study evaluates the operational effects of BRT implementation in Örebro using two key performance indicators: travel time and operating speed. Both indicators are calculated from a common set of cleaned, study area-matched GPS observations, described in detail in the Travel Time subsection below and then applied directly in the *Operating Speed* analysis.

5.3.1 PERFORMANCE INDICATORS & EVALUATION APPROACH

For each indicator, results are presented with the median as the primary statistic, supplemented by the mean, standard deviation, and the 5th and 95th percentiles to capture variability (*Section 4.2*). Changes between 2025 and 2025 are assessed using the Mann-Whitney U test (Mann & Whitney, 1947), applied to both indicators across both service groups (*Section 5.1.3*) and all three timeslots (*Section 5.1.2*). The Operating Speed subsection provides full details of the test procedure.

TRAVEL TIME

Travel time was calculated from GPS positions, which were consolidated to one observation per vehicle per minute by retaining the earliest ping within each minute. This approach addressed the duplicate-record pulling behaviour described in *Section 5.2.1*. For each pair of consecutive, deduplicated positions within the same trip, the elapsed time and distance were used to compute an implied speed. Only pairs with elapsed times between 1 and 120 seconds were retained, and any implied speeds exceeding 120 km/h were excluded as physically implausible. Each retained segment was then mapped along the corridor using linear referencing (*Section 5.2.2*). The segment's position along the corridor centreline was determined using `ST_LineLocatePoint` in PostGIS and assigned to the corresponding grid cell; observations more than 12.5 metres perpendicular to the centreline were excluded from further analysis.

For each trip, the total corridor travel time was calculated by summing the elapsed time across every retained consecutive segment pair within that trip. This is equivalent to measuring the time between the trip's first and last matched positions on the corridor. Because this method sums the actual elapsed time between observed positions, it necessarily includes any time when the vehicle was stationary along the corridor, such as stops or signals. As a result, the measure reflects the total time required to traverse the corridor, rather than only the time spent in motion.

Trips with a total travel time less than or equal to zero, or greater than 1,800 seconds, were removed as outliers.

Not every trip in the dataset covers the entire corridor. Some routes, especially Small Trunk lines, cover only a portion of the corridor (*Section 5.1.3*). To exclude incomplete trips without discarding genuinely short ones, a completeness threshold was calculated separately for each route and for each year. This threshold was based on the 90th percentile of the number of distinct grid cells a trip touched; trips covering less than 60% of this threshold were excluded. This specific combination was determined through exploratory inspection of the distribution of grid cells covered per trip, rather than derived from prior literature or formal sensitivity testing. It was selected as a pragmatic cutoff that excluded visibly incomplete or fragmented trips while retaining genuinely short ones (the sensitivity of this threshold was not formally tested). Calculating the threshold separately by year, rather than pooling both years together, was essential because bus line alignments were redesigned as part of the BRT implementation between the

two study periods. Pooling both years would risk evaluating trips against a route length that no longer applied.

For each route, group, year, and timeslot, the mean, median, standard deviation, and 5th and 95th percentile travel times were calculated directly from these trip-level totals. To determine whether the change in median travel time between 2023 and 2025 was statistically significant, the Mann-Whitney U test (Mann & Whitney, 1947). The Operating Speed section below provides the full rationale, tie-correction procedure, and normal-approximation method, which were identical for both indicators.

To characterise how much of the corridor each group's trips covered on average, the average number of distinct grid cells touched per trip was also calculated for each group and year, using the same segment counts as for the completeness threshold. This measure provides important context for the travel time results presented in *Section 6* as redesigned line alignments mean that the physical extent of corridor covered by a given group's trips is not necessarily identical between the two study periods.

OPERATING SPEED

Operating speed was calculated using the same deduplicated, corridor-matched segments described in the Travel Time section above, ensuring that both indicators were derived from an identical set of cleaned observations. Each retained segment's implied speed (distance divided by elapsed time, as described above) was used directly as an individual speed observation.

For each grid cell, route, year, and timeslot, the mean, median, standard deviation, and 5th and 95th percentile speeds were calculated from all valid segment-level speed observations assigned to that cell. These statistics were then combined into system- and group-level summaries using a weighted average across cells, with weights proportional to the number of observations per cell. Because the values being averaged are already statistics rather than raw observations, this weighted combination is an approximation rather than a precise recomputation from all underlying data. This represents a limitation of the aggregate (though not the grid-cell-level) figures.

To assess whether the difference in median speed between 2023 and 2025 was statistically significant, the Mann-Whitney U test was applied to each group and timeslot combination (Mann & Whitney, 1947), using every

individual segment-level speed observation. The Mann-Whitney U test was chosen over a t-test because operating speed observations are not expected to follow a normal distribution: they reflect a mix of free-flowing movement and near-stationary readings at stops and signals, resulting in a distribution better characterised by its median than by its mean (*Section 4.2*). The Mann-Whitney test assesses a shift in distribution without assuming normality (Hollander, Wolfe & Chicken, 2014), aligning the significance test with the median-based reporting (the same procedure used for travel time above). Given the large sample sizes involved (reported alongside each result in *Section 6*), the U statistic's distribution was approximated as normal, with the standard tie-correction applied (*Section 4.2*). Significance was determined by comparing the resulting z-statistic against standard normal critical values ($|z| \geq 1.960$ for $p<0.05$, $|z| \geq 2.576$ for $p<0.01$, $|z| \geq 3.291$ for $p<0.001$).

5.3.2 Analysis & Comparison

This step takes as input the mean, standard deviation, and 5^{th}/95^{th} percentile travel time and operating speed, calculated separately by route, service group, year, and timeslot, together with the corresponding Mann-Whitney U test results for each comparison (*Section 4.2.1*). These are compared across three dimensions: between the 2023 and 2025 measurement periods (to assess change over time), between the Trunk and Small Trunk service groups (to assess the effect of full versus partial exposure to the intervention), and spatially across 25-metre grid cells along the corridor (to assess where along the corridor changes occurred, rather than only whether they occurred network-wide).

Reductions in travel time and increases in operating speed indicate greater system efficiency. Reduced standard deviation and a narrower 5^{th}–95^{th} percentile range indicate greater consistency and reduced exposure to extreme delays. Statistical significance of each comparison is assessed using the Mann-Whitney U test, rather than assumed from the direction of change alone.

Analysing travel time and operating speed together, rather than in isolation, allows the study to distinguish genuine operational improvement (faster movement along the corridor) from other contributing factors, such as changes in the physical extent of the corridor covered by a service group's route (*Section 6.2.3*).

6 RESULTS & ANALYSIS

The results are discussed in the context of BRT as a collection of integrated priority measures rather than as a single, uniform system. In Örebro, BRT principles have been applied gradually and in part, so different bus segments and lines experience varying levels of intervention.

As a result, this analysis examines not just overall changes in performance but also how these changes vary with the extent to which each line is exposed to features such as dedicated bus lanes and signal prioritisation. This distinction matters when comparing trunk lines, which run continuously along corridors with interventions, and smaller trunk lines, which benefit from these measures only on certain sections.

Organising the results in this way visualises both the overall effects of the intervention and the extent to which those effects depend on the continuity and intensity of the BRT measures.

6.1 DATA QUALITY

Following the validation procedure outlined in *Section 5.2.1*, the physical-centric dataset was assessed against all nine error categories. *Table 6:1* presents a summary of the results, detailing both the number and proportion of records affected in each category.

Table 6:1. Summary of Documented Errors in the Physical-Centric Dataset.

Error Type	Details	Count	% of dataset
Missing Vehicle ID	Vehicle identification is missing	0	0.00%
Missing Position	Latitude or longitude is missing	0	0.00%
Missing Timestamp	Timestamp is missing	0	0.00%
Invalid Coordinates	Coordinates outside expected region	0	0.00%
Exact Duplicate Position	Repeated identical record for the same vehicle/trip/timestamp	30,460,642	24.19%
Contradictory position	Same vehicle/trip/timestamp reports more than one distinct position	29	~0.00%
Time Backwards	Timestamp decreased for the same vehicle	0	0.00%
Unrealistic Movement	Implied speed exceeds plausible bus speed (possible GPS error)	0	0.00%
Multiple Trips per Vehicle	Vehicle assigned to multiple trips at the same timestamp	0	0.00%

The physical-centric dataset exhibited no missing values in required fields, no coordinates outside the region, no backward time movement, no implausible speeds, and no instances of a vehicle being simultaneously assigned to multiple trips. The only substantive finding is a high rate of repeated records at identical timestamps: 24.19% of the dataset consists of exact duplicates, in which the same position was reported multiple times. Given the scale and consistency of this error, it most likely reflects the polling characteristics of the AVL feed: the underlying vehicle position remained unchanged between successive polls, leading to identical records being transmitted rather than a data error. This interpretation is further supported by the near-complete absence of contradictory records: only 29 cases (<0.01%) showed repeated records at the same timestamp reporting different positions, which would indicate a genuine fault rather than redundant polling. Because exact duplicates were assessed as a structural characteristic of the feed rather than a data quality defect, they were not removed at this stage; where a single unique observation per timestamp was later required (see *Section 5.2.1* and *5.3.1*), this was achieved in that step rather than by deleting them here.

In addition to these checks, recorded vehicle positions included movement falling outside the defined study area (such as segments of routes lying beyond the study area, or GPS positions offset from the road network), which the validation checks in *Table 6:1* do not themselves address, since they concern the correctness of individual records rather than their relevance to the area under study. A spatial filter was therefore applied by matching positions against the route geometry described in *Section 5.2.2*, retaining only those within ±12.5 metres of the corresponding route line. *Figure 6:1* and *Figure 6*:2 illustrate the effect of this filtering for bus line 1 in 2025, showing recorded vehicle positions before and after the filter was applied.

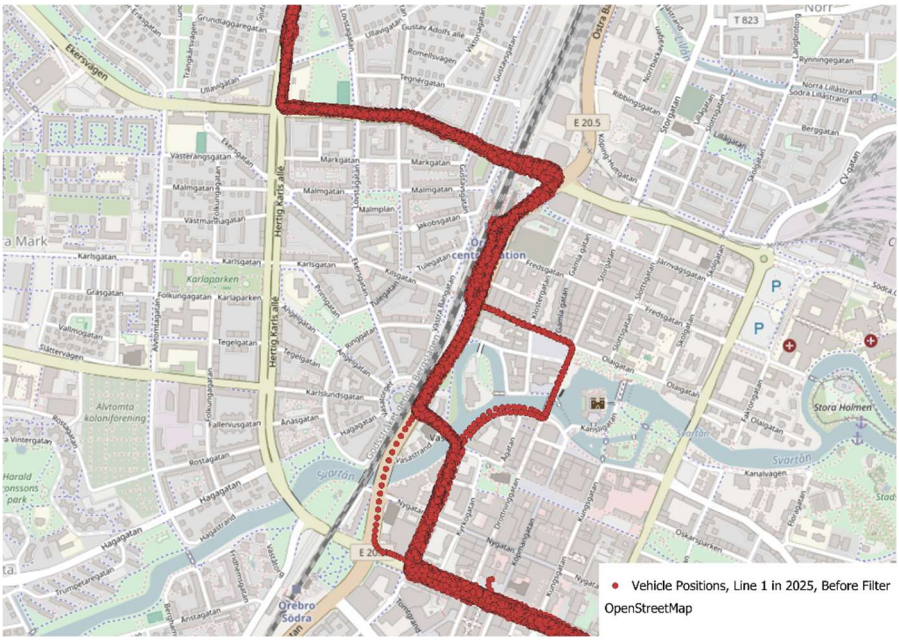


Figure 6:1. The Spatially Unfiltered Vehicle Positions for Bus Line 1 in 2025.

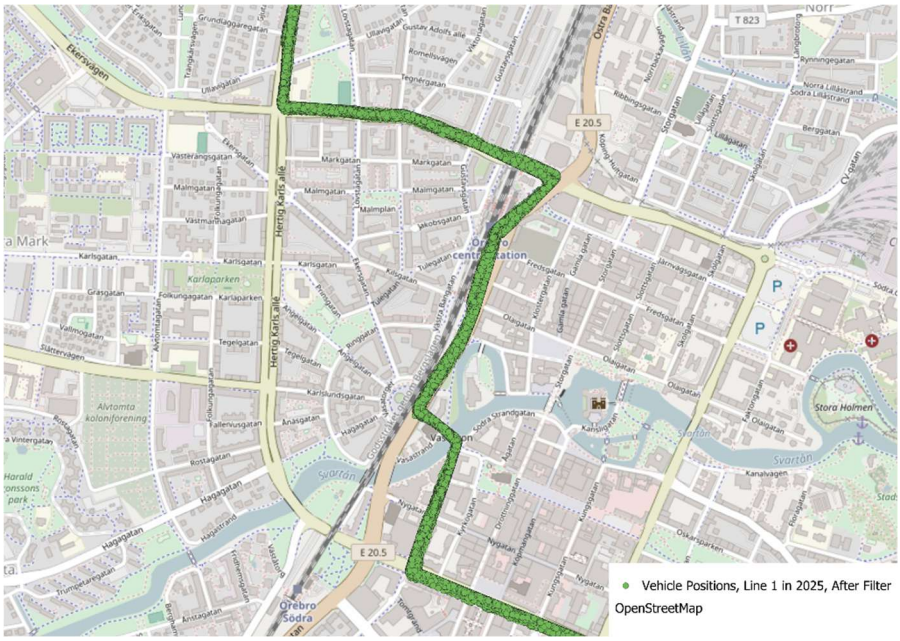


Figure 6:2. The Spatially Filtered Vehicle Positions for Bus Line 1 in 2025.

Comparing the two figures shows that the unfiltered data (*Figure 6:1*) includes positions extending beyond the study area boundary (see *Figure 5:4*), consistent with the vehicle's route continuing outside the study area (see route of bus line 1 in 2025 in *Figure 5:2*). After filtering (*Figure 6:2*), retained positions are concentrated along the corridor itself, indicating that the spatial filter successfully isolates the segment of each trip relevant to this analysis.

Throughout the next section, all travel time and operating speed results are limited to the parts of each service line's route that lie within the study area. Any performance beyond the boundaries of the area falls outside of the scope of this analysis. The distinction between Trunk and Small Trunk groups is based on the extent to which each line's route overlaps with the area, and this overlap changed between 2023 and 2025 as routes were redrawn as part of the broader BRT implementation.

6.2 Travel Time

This section considers travel time as the main indicator of how quickly passengers move along each corridor. Because BRT measures were

implemented with different levels of intensity and continuity across the network, travel time is analysed separately for the Trunk service lines (where buses run continuously along corridors with dedicated infrastructure) and the Small Trunk service lines, which benefit from these measures only on certain sections. For each group, travel time is compared between the 2023 and 2025 measurement periods across three timeslots (Morning Peak, Afternoon Peak, and Night Period), using both descriptive statistics and the Mann-Whitney U test to assess statistical significance.

6.2.1 TRUNK SERVICE LINES

Table 6:2 presents the number of observed trips alongside the mean, median, standard deviation, and 5th/95th percentile travel time for the Trunk service lines in each timeslot.

Table 6:2. Travel Time Statistics for Trunk Service Lines, 2023 and 2025 [km/h].

Year	Timeslot	Trips	Mean	Median [P05–P95]	SD
2023	AM peak	192	8.11	8.28 [4.83–11.15]	1.98
	PM peak	225	8.90	8.63 [5.00–13.28]	2.58
	Night	276	8.05	7.84 [5.20–11.75]	1.94
2025	AM peak	399	6.81	6.65*** [3.88–9.92]	1.9
	PM peak	416	6.84	6.72*** [3.79–10.57]	2.03
	Night	516	5.56	5.27*** [3.23–8.99]	1.86

*Note: Significance tested via Mann-Whitney U test. * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$.*

Across all timeslots, median travel time on the Trunk lines fell between 2023 and 2025 ($p < 0.001$; *Appendix B*), with a reduction ranging from 19.6% during the Morning Peak to 32.8% during the Night Period. Reliability improved as well: the standard deviation declined in every timeslot (Morning Peak from 1.98 to 1.90 minutes, Afternoon Peak from 2.58 to 2.03 minutes, Night Period from 1.94 to 1.86 minutes), and the P_{05}–P_{95} range narrowed accordingly. *Section 6.2.3* compares this result against the Small Trunk lines.

6.2.2 SMALL TRUNK SERVICE LINES

The same analysis was repeated for the Small Trunk service lines. *Table 6:3* presents the relevant statistics.

Table 6:3. Travel Time Statistics for Small Trunk Service Lines, 2023 and 2025 [km/h].

Year	Timeslot	Trips	Mean	Median [P05–P95]	SD
2023	AM peak	192	8.11	5.15 [2.97–7.85]	1.48
	PM peak	225	8.90	5.07 [2.43–7.87]	1.70
	Night	276	8.05	5.18 [2.80–7.73]	1.60
2025	AM peak	399	6.81	4.33*** [208.00–7.16]	1.64
	PM peak	416	6.84	4.02*** [2.03–7.55]	1.76
	Night	516	5.56	3.20*** [1.65–5.65]	1.35

*Note: Significance tested via Mann-Whitney U test. * p < 0.05, ** p < 0.01, *** p < 0.001.*

Like the Trunk lines, the median travel time for Small Trunk decreased across all timeslots ($p < 0.001$: *Appendix C*), with the largest reduction occurring during the Night Period (38.2%). Reliability followed a more mixed pattern: the standard deviation increased during the Morning Peak (from 1.48 to 1.64 minutes) and Afternoon Peak (from 1.70 to 1.76 minutes) and decreased only during the Night Period (from 1.60 to 1.35 minutes). *Section 6.2.3* compares this result directly against the Trunk lines.

6.2.3 Comparison Between Service Groups

Table 6:2 through *Table 6*:3 demonstrate that both service groups saw statistically significant improvements in median travel time across all three timeslots. *Figure 6:3* compares the magnitude of these changes directly.

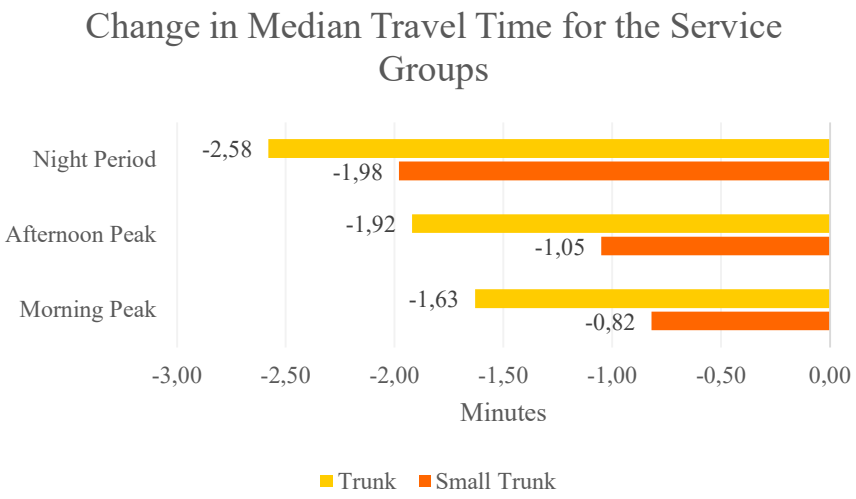


Figure 6:3. Comparison between Travel Time Statistics during the different Timeslots for the Service Groups.

Figure 6:3 illustrates that Trunk lines improved by approximately twice as much as Small Trunk lines in every timeslot (for example, a reduction of 2.58 minutes at Night Period for Trunk, compared to 1.98 minutes for Small Trunk). Since Trunk lines are continuously exposed to BRT measures along the entire corridor, while Small Trunk lines intersect only a shorter segment of the same fixed corridor, this pattern aligns with a dose-response relationship: greater exposure to BRT infrastructure is linked to a proportionally greater reduction in travel time. Both groups display the same order of improvement across timeslots, with the smallest gain during the Morning Peak and the largest during the Night Period. This suggests that the timing of the benefit is driven by a factor affecting the entire corridor (such as background congestion during peak hours) rather than exposure level alone.

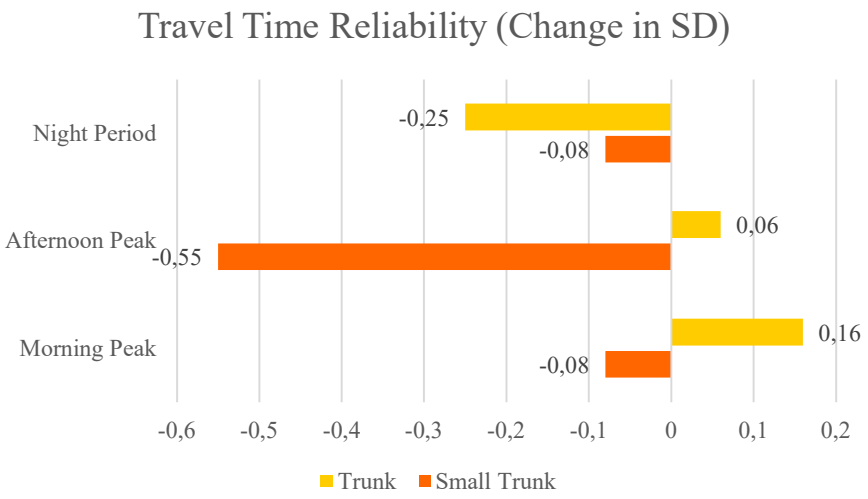


Figure 6:4. Change in Travel Time Reliability.

Reliability, in contrast, sets the two groups apart: the standard deviation for Trunk decreased in every timeslot (as seen in *Figure 6:4*), whereas for Small Trunk it increased in two out of three. This suggests that full exposure to BRT measures leads to more comprehensive improvement (faster and more consistent service), while partial exposure yields a faster typical trip but not the same gains in predictability.

The corridor and the Trunk/Small Trunk grouping are both fixed; what changed between 2023 and 2025 is the routes themselves, redrawn as part of the same BRT implementation, altering how much of the fixed corridor each line's alignment intersects. *Table 6:4* quantifies this directly.

Table 6:4. Average Corridor Segments covered per Trip, 2023 vs 2025.

Group	Segments 2023	Segments 2025	% change
Trunk	57.06	50.81	-11.0%
Small Trunk	26.97	16.96	-37.5%

On average, trips on the Trunk corridor in 2025 covered 11.0% fewer 25-metre segments than in 2023, while Small Trunk trips covered 37.5% fewer. Because travel time here is measured as the distance between the southernmost and northernmost points reached by each trip, a smaller intersection with the corridor reduces measured travel time regardless of any change in operating speed. Thus, improvements in travel time should be understood as the combined result of two mechanisms brought about by

the BRT implementation: genuinely faster operation and a reduced span of corridor covered. *Section 6.3* explores how these two mechanisms contributed differently to each service group.

Travel time improved markedly for both service groups across all three timeslots, reflecting a combination of faster operations and a reduced span of corridor covered after the 2025 route redesign. Trunk lines achieved roughly twice the median improvement seen in Small Trunk lines and also exhibited a consistent improvement in reliability (a pattern not observed for Small Trunk). *Section 6.3* investigates whether operating speed follows a similarly consistent pattern and seeks to disentangle the contributions of the two mechanisms identified above.

6.3 Operating Speed

This section considers operating speed to better understand how efficiently buses traverse the corridor. Changes in average speed provide a clear, measurable indicator of the impact dedicated bus lanes have on overall traffic flow. When average operating speed increases, it suggests buses encounter fewer delays and move more smoothly through the network, supporting the travel-time interpretation discussed previously.

Operating speed is calculated from individual point-to-point GPS observations along the corridor, rather than on a per-trip basis, resulting in much larger sample sizes than those in *Section 6.2*. In every group and timeslot, the 5th percentile speed is 0 km/h. This is not an anomaly; it reflects genuine stationary periods (such as layovers at the corridor's endpoints) captured in the underlying GPS data.

6.3.1 Trunk Service Lines

Table 6:5 presents the descriptive statistics for operating speed on the Trunk service lines.

Table 6:5. Significance of Operating Speed Change for Trunk Service Lines, 2023-2025 [km/h].

Year	Timeslot	Obs.	Mean	Median [P05–P95]	SD
2023	AM peak	1587	9.40	8.75 [0.00–27.53]	9.39
	PM peak	2065	8.64	7.26 [0.00–25.50]	8.69
	Night	2247	9.57	8.04 [0.00–30.00]	10.34
2025	AM peak	2758	9.81	10.11*** [0.00–21.23]	6.97
	PM peak	2925	9.67	9.82*** [0.00–21.75]	7.11
	Night	2990	11.27	11.45*** [0.00–22.77]	7.16

Median operating speed on the Trunk lines increased in every timeslot, with reliability improving as well ($p < 0.001$: *Appendix D*), and reliability improved alongside it: standard deviation decreased from 9.39 to 6.97 km/h in the Morning Peak, from 8.69 to 7.11 km/h in the Afternoon Peak, and from 10.34 to 7.16 km/h in the Night Period (mirroring the consistent gains in reliability observed for travel time in *Section 6.2.1*). *Figure 6:5* through *Figure 6:7* present spatial maps of this change for each timeslot, beginning with the Morning Peak.

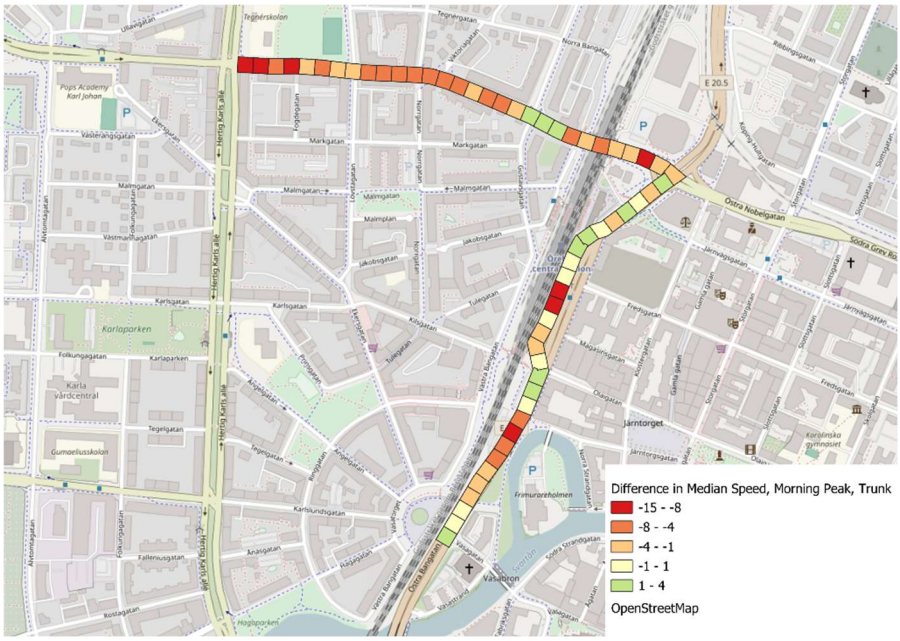


Figure 6:5. Difference in Operational Speed in 2025 compared to 2023 during the Morning Peak for Trunk Service Lines [in km/h].

Figure 6:5 reveals that the network-wide increase in Morning Peak median speed is not distributed evenly along the corridor. Much of the route experiences a decrease in speed, while the overall positive result is driven by a smaller number of segments with substantial speed increases. *Figure 6:6* shows a similar pattern for the Afternoon Peak.

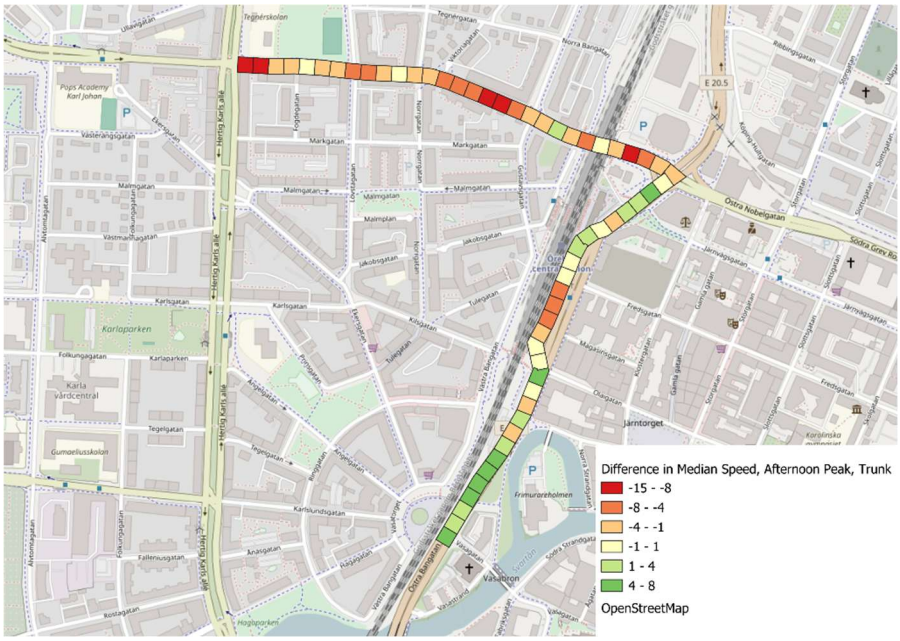


Figure 6:6. Difference in Operational Speed in 2025 compared to 2023 during the Afternoon Peak for Trunk Services [in km/h].

A similar spatial pattern emerges for the Afternoon Peak, with the same section of the corridor again exhibiting the most pronounced speed decrease. *Figure 6:7* displays the results for the Night Period.

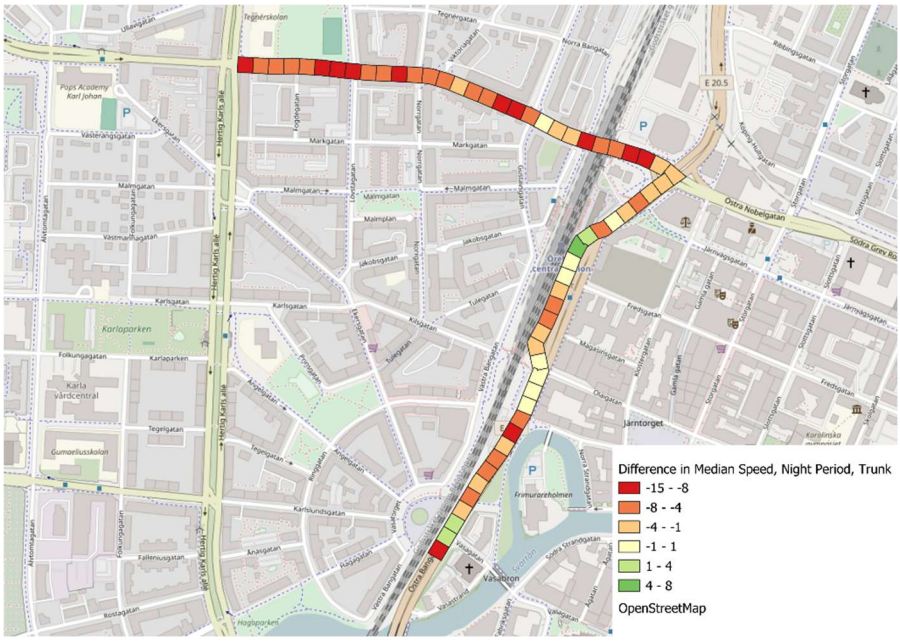


Figure 6:7. Difference in Operational Speed in 2025 compared to 2023 during the Night Period for Trunk Services [in km/h].

Across all three timeslots, the same portion of the corridor consistently shows the largest speed decreases, while a smaller section exhibits the greatest gains. This recurring spatial pattern suggests that the overall speed improvement is concentrated in specific parts of the corridor rather than uniform. At least one identifiable section appears not to have benefited from the intervention to the same extent as the rest of the line. Pinpointing this location (by cross-referencing the affected segment with the corridor's infrastructure map) would strengthen this finding considerably.

Operating speed on the Trunk lines improved significantly and became more consistent in every timeslot, mirroring the travel time results from *Section 6.2.1*. However, the spatial maps reveal that these improvements are not evenly distributed: a particular recurring section of the corridor shows a speed decrease across all three timeslots, while the overall gain is driven by greater improvements in other segments.

6.3.2 Small Trunk Service Lines

Table 6:6 presents the descriptive statistics for operating speed on the Small Trunk service lines.

Table 6:6. Significance of Operating Speed Change for Small Trunk Service Lines, 2023-2025 [km/h].

Year	Timeslot	Obs.	Mean	Median [P05–P95]	SD
2023	AM peak	934	6.57	5.47 [0.00–17.44]	6.52
	PM peak	1142	6.58	5.76 [0.00–17.50]	6.31
	Night	1537	6.4	3.72 [0.00–18.86]	7.05
2025	AM peak	1433	5.49	2.44*** [0.00–19.16]	6.91
	PM peak	1536	5.45	3.00*** [0.00–17.63]	6.41
	Night	1104	7.47	5.50*** [0.00–22.71]	7.96

In contrast to the Trunk lines, the standard deviation increased in every timeslot for the Small Trunk group, including the Night Period (from 7.05 to 7.96 km/h), which was the only timeslot where median speed improved. As a result, no timeslot showed both faster and more consistent speeds.

Operating speed on the Small Trunk lines decreased significantly during both the Morning Peak (−55.3%) and Afternoon Peak (−47.9%) and increased only during the Night Period (+47.8%; *Appendix E*). This is a notable contrast to the travel time findings in *Section 6.2.2*, where all three timeslots showed significant improvement. As outlined in *Section 6.2.3*, the span of the fixed BRT corridor covered by Small Trunk trips was smaller in 2025 than in 2023 (a 37.5% reduction in matched segments, *Table 6:4*), which results from the redrawn 2025 alignment rather than a physical shortening of the corridor itself. Since travel time is measured as the distance between the southernmost and northernmost points reached by each trip, this smaller intersection reduces measured travel time independently of operating speed. This explains why travel time improved for Small Trunk even as median operating speed decreased during Morning and Afternoon Peak. *Figure 6:8* through *Figure 6:10* present the spatial mapping of these changes, starting with Morning Peak.

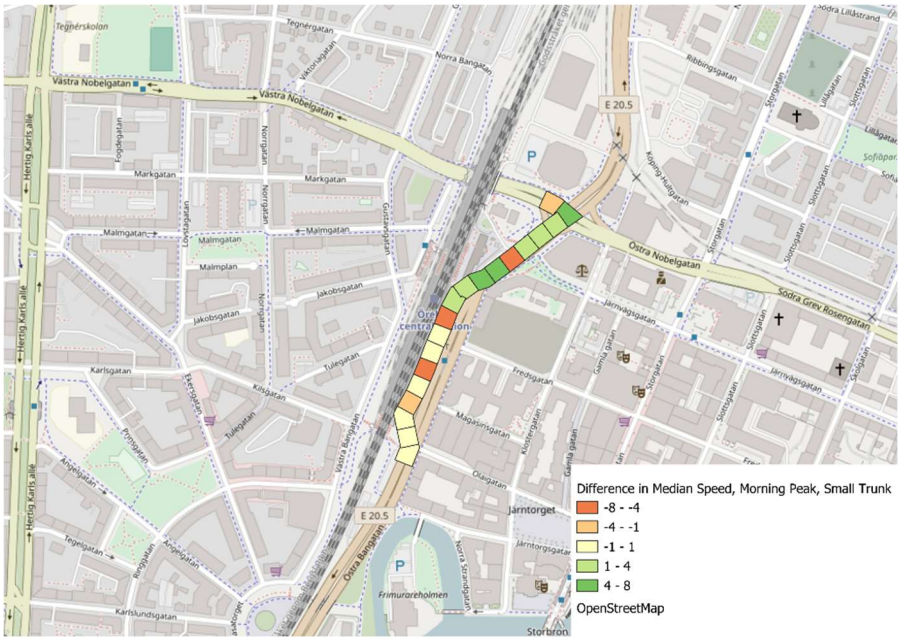


Figure 6:8. Difference in Operational Speed in 2025 compared to 2023 during the Morning Peak for Small Trunk Services [in km/h].

Figure 6:8 demonstrates that the speed decrease is broadly distributed across most of the mapped Small Trunk section during the Morning Peak. *Figure 6:9* reveals a similar pattern for the Afternoon Peak.

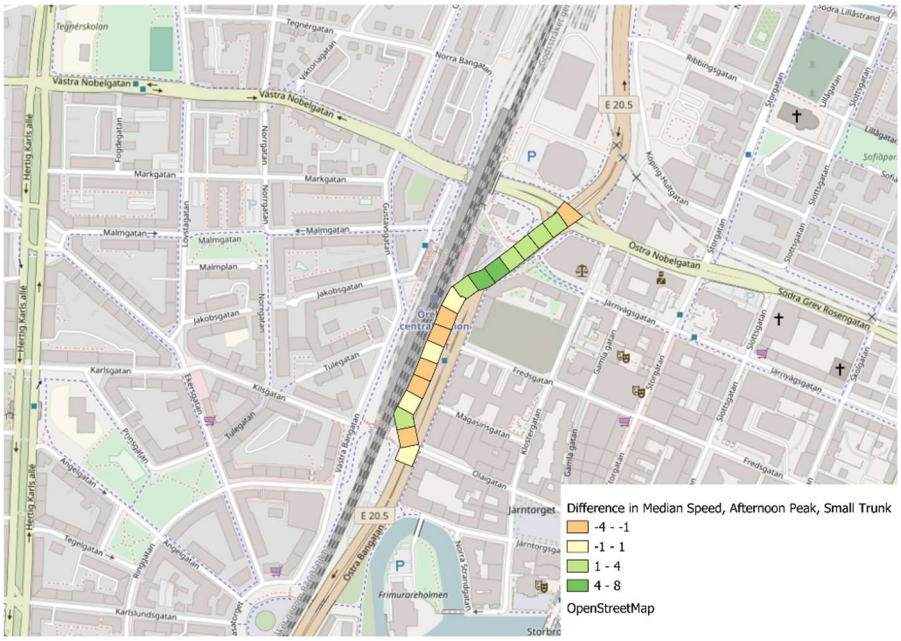


Figure 6:9. Difference in Operational Speed in 2025 compared to 2023 during the Afternoon Peak for Small Trunk Services [in km/h].

The Afternoon Peak map reveals the same trend as the Morning Peak, with most of the corridor exhibiting a speed decrease. *Figure 6:10* presents the Night Period, where the overall trend reverses direction.

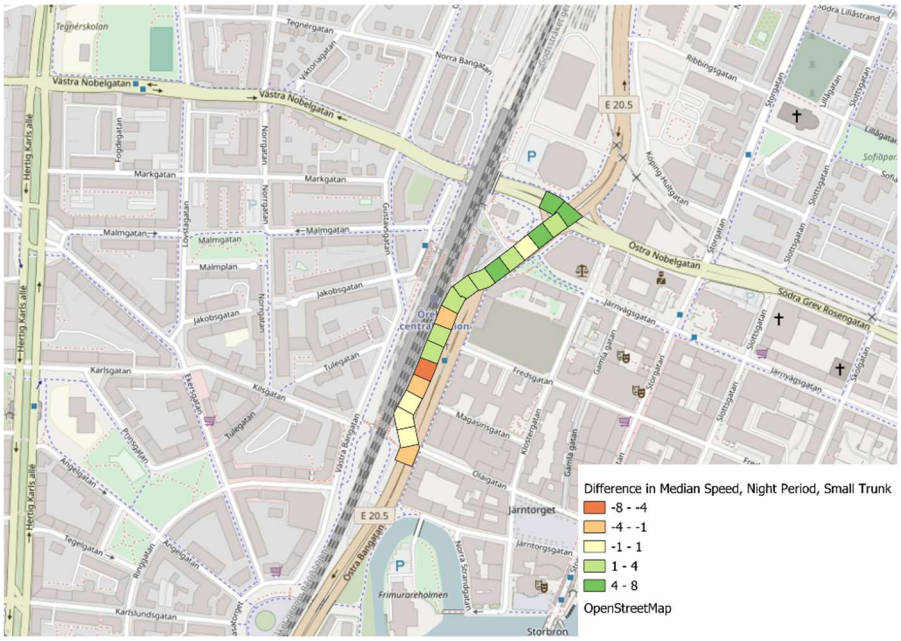


Figure 6:10. Difference in Operational Speed in 2025 compared to 2023 during the Night Period for Small Trunk Services [in km/h].

Figure 6:10 shows mostly green segments, reflecting the significant increase in speed during the Night Period as reported in *Table 6:6*. However, as noted above, this is also the timeslot when speed became less consistent (SD increased from 7.05 to 7.96 km/h; *Appendix E*), so the median improvement should not be interpreted as an unqualified benefit for passengers. *Section 6.3.3* reconciles this pattern, along with the Morning and Afternoon Peak decreases shown in *Figure 6:8* and *Figure 6*:9, with the travel time results from *Section 6.2.2*, and draws a direct comparison with the trunk service lines.

Operating speed on the Small Trunk lines decreased significantly during both peak periods, even as travel time improved in those same periods, and reliability worsened in every timeslot—including the Night Period, which was the only timeslot where median speed increased. *Section 6.3.3* directly compares these results to those of the Trunk service lines.

6.3.3 Comparison Between Service Groups

Table 6:5 and *Table 6:6* show that operating speed changed in opposite directions between the two service groups during Morning and Afternoon Peak, while both groups improved during the Night Period. *Figure 6:11* directly compares the magnitude and direction of these changes.

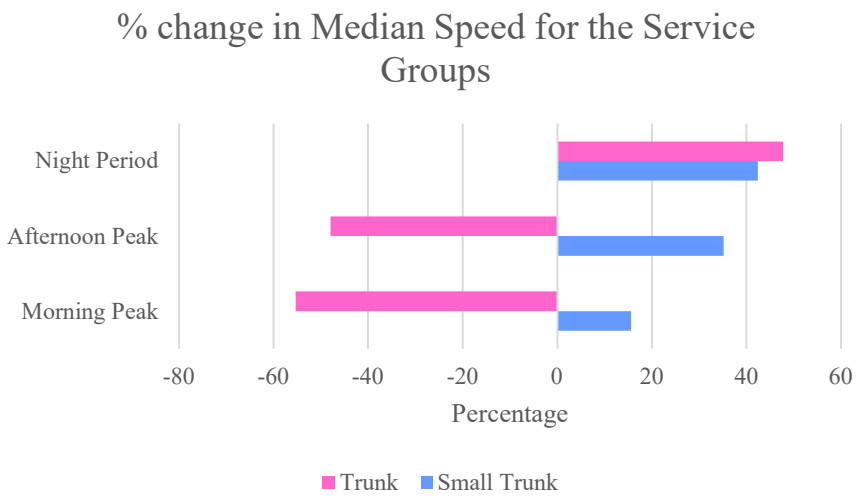


Figure 6:11. Change in % in Median Speed, grouped by Timeslot and Service Groups [km/h].

Figure 6:11 demonstrates that Trunk's operating speed improved in every timeslot, while Small Trunk's speed declined sharply during both peak periods and increased only at Night, the same timeslot in which Small Trunk's trip volume decreased (from 1,537 to 1,104 observations, *Table 6:6*), a pattern that may be related to reduced congestion exposure outside peak hours.

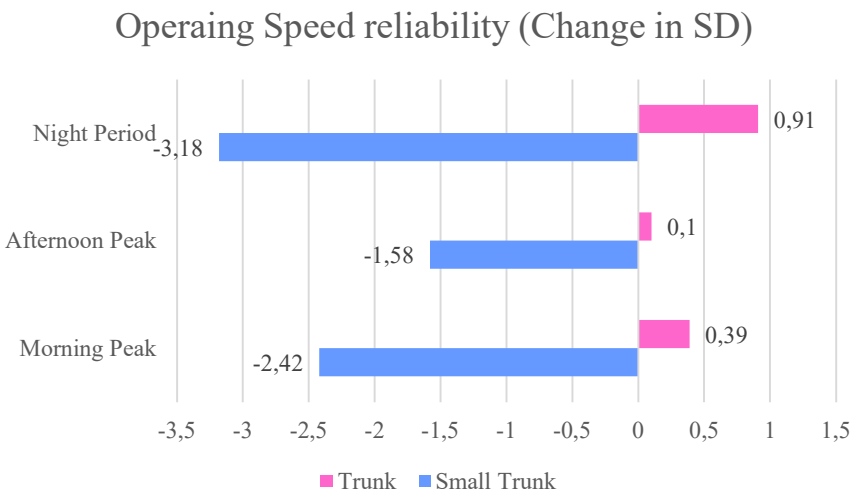


Figure 6:12. Change in Operating Speed Reliability.

The reliability findings from *Figure 6:12* reinforce this divergence: Trunk became more consistent and faster in every timeslot, whereas Small Trunk became less consistent, even when median speed improved. For Small Trunk, the travel time benefit during peak hours therefore seems to result primarily from the reduced corridor span identified in *Section 6.2.3*, rather than from faster or more reliable movement along the treated segments.

Operating speed increased significantly and became more consistent in every timeslot for the Trunk service lines. In contrast, Small Trunk lines showed the opposite pattern in reliability, along with a significant speed decrease during both peak periods, even though travel time improved for both groups throughout *Section 6.2*. Placing these findings alongside the corridor-span results from *Section 6.2.3* reveals that the two service groups benefited from BRT implementation through substantially different mechanisms: full corridor exposure (Trunk) resulted in genuinely faster and more reliable operations. In contrast, partial exposure (Small Trunk) delivered a faster typical trip mainly by reducing the corridor span covered, without a corresponding gain in how consistently or quickly buses moved. This distinction directly addresses the exposure question at the heart of this chapter's analysis.

7 DISCUSSION

This chapter interprets the results presented in *Section 6*, connecting them to the study's research questions and situating them within the broader scholarly conversation about dedicated bus lane and BRT interventions.

7.1 EFFECT ON TRAVEL TIME & OPERATING SPEED

While it is often assumed that the effects of dedicated bus lanes are modest or inconsistent (*Section 3.2*), the findings here demonstrate a clear and statistically significant improvement in both travel time and operating speed for both service groups, across all three timeslots studied. Median travel time decreased by 19.6–38.3%, depending on group and timeslot (*Section 6.2*), and median operating speed increased by as much as 42.4% for the Trunk lines (*Section 6.3.1*). This effect is both stronger and more consistent than what is commonly reported in the literature on partial or incremental BRT implementations (Levinson et al., 2003), a point explored further in *Section 7.2* regarding the maturity of Örebro's implementation.

The findings also show that the two indicators (travel time and operating speed) do not always follow the same patterns, and that this divergence is informative rather than a limitation to overlook. For the Trunk lines, travel time, operating speed, and reliability all improved together in every timeslot (*Sections 6.2.1, 6.3.1*), showing a consistent trend across all measured indicators. In contrast, for the Small Trunk lines, travel time improved in all timeslots, but operating speed decreased significantly during both peak periods (*Section 6.3.2*). A closer examination (*Section 6.2.3, Table 6:4*) shows that the 2025 route redesign reduced the fixed corridor covered by Small Trunk trips by 37.5%, while it reduced the corridor covered by Trunk lines by only 11.0%. Since travel time is measured as the time needed to traverse whichever span of the corridor a trip covers, a shorter span reduces travel time independently of bus speed. Specifically for Small Trunk during peak hours, the observed travel time improvement appears to result largely from a shorter route rather than from faster operation, a substantially different mechanism than for the Trunk lines, and one not visible from travel time data alone.

7.2 Exposure, Dose-Response & System Maturity

One central insight from this study is that the extent of improvement is closely linked to exposure to BRT infrastructure. Trunk lines, which benefit from continuous exposure along the entire corridor, experienced about twice the median travel time improvement compared to Small Trunk lines, which intersect only a shorter segment of the same corridor (*Section 6.2.2*). This dose-response relationship aligns with the theoretical expectation that dedicated infrastructure yields benefit in proportion to the amount of the route it covers (*Section 4*). It also offers direct empirical support for considering exposure level as a key explanatory factor in BRT evaluations, rather than relying solely on network-wide averages.

This finding is particularly striking given that Örebro's BRT implementation is still in progress: Phase 2 has yet to commence, and several Phase 1 sections were completed only recently, between 2024 and 2025 (*Section 2.2.1*). The fact that a partially completed system is already generating significant improvements (rather than the modest or negligible effects sometimes reported for early-stage BRT projects) suggests the measures implemented so far are operationally effective. It is reasonable to anticipate further gains as the remaining sections are completed and the system stabilises. However, this interpretation should be viewed as plausible rather than definitive, since the study cannot directly observe how performance will evolve as the system matures; this will require the longer time series outlined in *Section 9*.

7.3 Reliability & Local Variations

Reliability (measured in this study as the standard deviation of travel time and operating speed, rather than headway) differentiates the two service groups more distinctly than measures of central tendency alone. The Trunk lines demonstrated improved reliability in every timeslot for both travel time and speed, with no exceptions (*Sections 6.2.1, 6.3.1*). In contrast, the Small Trunk lines displayed a mixed pattern and, for speed, a consistently negative one: standard deviation increased in every timeslot, even during the Night Period, the only timeslot with an increase in median speed (*Section 6.3.2*). Consequently, there is no timeslot in which Small Trunk lines became both faster and more consistent—a notably weaker outcome

than that for Trunk, and one that would not be visible by examining only median or percentage changes.

The spatial maps provided in *Sections 6.3.1* and *6.3.2* offer additional nuance. For the Trunk lines, a specific, recurring section of the corridor exhibited a decrease in speed across all three timeslots, even though the overall network result was positive (*Figure 6:5* - *Figure 6:*7). This indicates that the aggregate improvement is concentrated in certain segments, rather than being evenly distributed along the entire corridor. This finding directly supports the value of section-level (rather than solely corridor-wide) analysis for interpreting BRT effects. It also aligns with the expectation that outcomes depend on the specific infrastructure present at each location, such as signal priority, physical separation, and stop design, rather than treating the corridor as a uniform entity.

The Night Period result for the Small Trunk lines requires caution before interpreting it as a straightforward improvement. Three factors coincide here: median speed increased significantly (+47.8%), trip volume declined rather than increased (from 1,537 to 1,104 observations, the only timeslot in the dataset with this pattern), and reliability worsened (standard deviation rose from 7.05 to 7.96 km/h). Although *Figure 6:10* visually suggests a shift towards faster speeds across much of the mapped section, this impression has not been formally quantified (for example, by calculating the proportion of grid cells showing positive versus negative changes). Additionally, the smaller and potentially changed group of trips at night raises the possibility that the result reflects a shift in which trips or routes are present in the 2025 Night sample, rather than a genuine increase in speed for the same service. Determining whether the apparent Night Period improvement is robust (for instance, by assessing whether it is concentrated in a particular part of the route, as seen with the Trunk lines) remains an open question that the current maps cannot fully address. This limitation is noted here rather than resolved as a definitive finding.

7.4 Data Quality & Methodological Limitations

The data quality assessment (*Section 6.1*) found the AVL dataset to be structurally complete, with no missing fields, invalid coordinates, backward timestamps, or implausible speeds. The one substantive issue (24.19% exact duplicate records, resulting from the AVL feed's polling behaviour

rather than a data fault) required active correction rather than passive acknowledgement. Calculating raw point-to-point speed without first deduplicating to one observation per vehicle per minute produced a median speed of 0 km/h in nearly every group and timeslot, an artefact identified and corrected during the analysis (*Section 5.3.1*). This proved to be a meaningful methodological insight: a data quality issue that appeared minor in aggregate (24.19% of records) could, if unaddressed, completely invalidate the primary speed indicator. Standard validation checks, such as those in *Table 6:1*, would not have flagged this, as duplicate records are not inherently invalid. This highlights the need for data quality assurance in high-frequency AVL data to go beyond ensuring individual records are well-formed and to check that derived indicators behave plausibly. This insight is useful for any future study using similar structured AVL feeds.

A related limitation involves the corridor's redefinition between 2023 and 2025 (*Section 6.2.3*). Because route alignments changed as part of the same BRT implementation being evaluated, this study cannot fully distinguish between improvements due to “faster driving” and those due to a “shorter route,” especially for the Small Trunk lines. This is not a flaw in the analysis but rather an inherent aspect of assessing an intervention that altered both infrastructure and route design at the same time. However, it also means travel time improvement alone should not be interpreted as a pure measure of operational speed gain.

7.5 Overall Interpretation

Taken together, the results show that BRT implementation in Örebro has led to significant improvements in travel time for every service group and timeslot studied, and in operating speed for the Trunk lines specifically. This outcome is stronger than what one might expect from the common assumption of modest or inconsistent effects, especially given the rollout is still incomplete. The scale of benefit is closely tied to exposure: full corridor exposure yields approximately double the improvement compared to partial exposure, and it does so through genuinely faster and more reliable operations. In contrast, much of the improvement seen with partial exposure comes from a shorter measured route rather than increased speed. Reliability (not just central tendency) is key here; it most clearly distinguishes a genuine, comprehensive improvement from a partial and locally uncertain one. This focus on reliability represents one of the study's most original contributions.

8 CONCLUSION

This study evaluated the operational impacts of dedicated bus lanes in Örebro by comparing travel time and operating speed before and after introducing BRT-inspired measures, focusing on service lines with varying levels of exposure to these interventions. The results reveal significant improvements across nearly every indicator and timeslot examined, with both the magnitude and completeness of these improvements increasing with exposure to BRT infrastructure.

8.1 RESEARCH QUESTION 1: OPERATIONAL EFFECTS

Dedicated bus lanes in Örebro significantly reduced travel time for both Trunk and Small Trunk service lines across every timeslot studied ($p<0.001$ in all cases), with reductions ranging from 19.6% to 38.3%. Operating speed increased significantly for the Trunk lines in every timeslot, by up to 42.4%. For Small Trunk lines, however, operating speed decreased significantly during peak periods even as travel time improved, a divergence attributable to a substantial reduction in the corridor length covered by the redesigned routes rather than faster operation.

The effects varied clearly by exposure level: full corridor exposure (Trunk) produced roughly double the travel time improvement seen with partial exposure (Small Trunk) and resulted in uniform reliability improvements (something not observed with partial exposure). Effects also varied spatially within the corridor: the Trunk line's overall speed improvement masks a recurring section where speed decreased in every timeslot, demonstrating that BRT measures do not deliver uniform benefits along the entire corridor, even when present throughout its length.

8.2 RESEARCH QUESTION 2: DATA & VALIDATION

AVL data delivered via the GTFS-RT VehiclePositions feed proved suitable for this analysis but required careful, non-trivial processing before it could be relied upon. A structurally minor issue (repeated position records caused by the feed's polling behaviour) could invalidate the primary speed indicator entirely if not explicitly corrected, even though it passed all standard structural validation checks. This highlights that data quality assurance for high-frequency AVL data must involve assessing the

plausibility of derived indicators, not just the validity of individual raw records.

8.3 Research Question 3: Evaluation Method

The method developed in this study (combining travel time and operating speed, each summarised by both central tendency (median) and variability (standard deviation), tested for significance using the Mann-Whitney U test, and examined at both the corridor and 25-metre segment levels) proved capable of detecting effects that would have been missed by using a single indicator or a single spatial scale. Reliability distinguished a genuinely comprehensive improvement (Trunk) from a partial one (Small Trunk) in a way that central-tendency measures alone could not. Spatial disaggregation also revealed within-corridor differences that network-wide statistics would have obscured. The method is reproducible, relies entirely on SQL-based queries against the underlying AVL data, and applies to other cities with similar data availability.

8.4 Overall Conclusion

Dedicated bus lanes and associated BRT measures in Örebro have significantly improved travel time and, for continuously exposed service lines, operating speed and reliability. These effects are stronger than expected, given that implementation is not yet complete, suggesting that the measures already in place are operationally effective. The results also make it clear that the completeness of the benefit depends on the degree of exposure to BRT infrastructure: full exposure leads to a faster, more reliable, and more consistent service, while partial exposure delivers a faster typical trip but without the same improvements in consistency, and with at least some of that improvement due to a shorter measured route rather than faster operation. This distinction (between genuine operational improvement and improvement driven by other factors) emerged only because travel time, speed, and reliability were analysed together rather than in isolation, and it is the central methodological insight of this study for future BRT evaluations.

9 FUTURE WORK

Several promising directions exist for extending this study's findings.

A longer time series (spanning three to five years) would enable future research to capture how effects change as Örebro's BRT implementation matures and stabilises, since this study's results, although already robust, reflect a system that is not yet fully realised (*Section 7.2*). Relatedly, disentangling the specific contributions of individual measures such as signal priority, physical separation, and stop design at the section level would help explain the spatial heterogeneity observed in this study. This would be particularly valuable for understanding the recurring underperforming section identified for the Trunk lines (*Section 7.3*), as well as the open question regarding the representativeness of the Small Trunk Night Period result.

This study focused exclusively on operational indicators derived from vehicle position data and did not address how passengers experience these changes. Future research that incorporates passenger perceptions of regularity and travel time, alongside ridership data, would provide a more comprehensive understanding by linking operational improvements to the experiences of the people these interventions are meant to benefit. Additionally, combining this operational approach with traffic simulation models would make it possible to estimate the effects of not-yet-implemented measures (such as completing Phase 2 or extending physical separation to sections currently shared with mixed traffic) before they are built. This would provide decision-makers with a stronger evidence base for prioritising future investments.

Finally, since reliability emerged as one of the most informative indicators in this study (the factor that most clearly distinguished the comprehensive improvements on the Trunk lines from the partial gains on Small Trunk), future work could develop this dimension further. This might include examining day-to-day variability, rather than only within-period spread, investigating how performance changes during specific disruptions or incidents, and analysing whether peak congestion periods are shifting earlier or later in the day as the broader network adapts to the new infrastructure.

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APPENDIX

Appendix A. BRT-grading on Implementations in Örebro.

Category	Green Level – Description	Yellow Level – Description	Grading
Urban Design			**Yellow**
Urban Planning	Co-planning between BRT and development with an anchored strategy, complementary activities, services and development around stops and hubs.	Only some new development and densification at BRT stops.	Green
Urban Environment	Redevelopment/improvement of the street space, lighting, walking areas, plantings, street furniture.	Only some re-furnishment, reduction of car traffic, prioritisation of walking and cycling.	Yellow
The Interaction of Bus Stops with Buildings	The stops form an integrated part of the urban environment, with proximity to other city functions. Always high-quality bicycle parking and connections.	Stops near destinations/city buildings but not fully integrated. Good and pleasant walkways to stops.	Yellow
Line Drawing	Wide, smooth, through/centrally in residential and urban areas, no sharp curves. Less than 10 percent longer than the distance of the direct route between major stops.	Shortcuts – abbreviations, through7under roundabouts. Enter terminals in gentle turns, few sharp curves. Less than 20 percent longer than the straight-line distance between major stops	Yellow
Public Transport Infrastructure			**Green**
Right of way and signal prioritisation	Full signal priority with stops only at bus stops and with active steering for high regularity. No bicycles in the carriageways, no disruptive vehicles, curb parking, or exits.	Signal priority along the entire line. Usually, no need to stop or slow traffic jams. Disturbing curb parking, exits, and bicycles in the carriageway only to a limited extent.	Green
Stop design	Straight entry, flat entry, marked door positions/handicapped entrance. Waiting area under cover the entire	Straight entrance (step stop), waiting area with weather protection, benches and stop information.	Green

	length of the bus, benches, stop information, bicycle parking, pedestrian and bicycle passage outside the waiting area.		
Identity	Own identity, attractive designed branding on vehicles, stops and information.	Custom marking/design on vehicles and stops.	Green
Design of Driveway/Privacy	Own or separate lanes/roads, lanes, restricted areas.	Dedicated lanes or guaranteed accessibility, certain separate roads, calm stops without disturbing fast car traffic.	Green
Marking of the Bus Route	Separated from car traffic with physical demarcation and a different colour of the roadway.	Lane marking with a wide, solid white line and the text “BUS”.	Green
Land cover and design	Smooth driving surface, no “culverts”. Moderate curves on separate bus routes.	No speed restrictions for the bus. Priority winter road maintenance.	Yellow
Bus Stop Distance in Built-Up Areas	500 – 800 m.	400 – 500 m or more than 800 m.	Green
Vehicles and Support Systems			**Green**
Vehicle	Adapted vehicles, wide doors, own design, extra smooth ride and very quiet, especially at stops. Flat entry, marked disabled entrance, automatic wheelchair ramp/”gap filler” if necessary.	Low-floor buses with wide doors. Boarding is possible at all doors. Quiet, especially at stops.	Green
Information on stops	Traffic info and a local area map with destination points. Activatable speaker, departure-time display, and active information during traffic disruptions.	Clear line numbers and destinations, a line network map, and real-time line information.	Green
Information in Vehicle	Real-time information, information about connections at upcoming stops and active information in case of disruptions.	Line map and info/stops announcements, including the next stop.	Green
Traffic Operation			**Green**

Reliability/Regularity	System that ensures even intervals between vehicles and no delay for the traveller.	Delay maximum half the frequency, maximum 1 time per hour.	Green
Bus Stop Times and Ticketing	Ticket/payment solution that does not affect stop time. Possible to buy a ticket at the stop. Less than one second for boarding and door.	Entry and exit at all doors, no advance warning; 1 – 1.5 seconds/entry and door.	Green
Daytime Time Frequency	Less than 8 minutes.	Less than 10 minutes.	Green
Frequency Off-Peak Traffic	Less than 15 minutes.	Less than 20 minutes.	Green
Traffic Day	At least 5 am to midnight.	At least from 6 am to 11 pm.	Green

Appendix B: Significance of Travel Time Change for Trunk Service Lines, 2023-2025.

Timeslot	Median 2023	Median 2025	Change	% change	p-value	Sig.
AM peak	8.28	6.65	-1.63	-19.6%	<0.001	***
PM peak	8.63	6.72	-1.92	-22.2%	<0.001	***
Night	7.84	5.27	-2.58	-32.8%	<0.001	***

*Significance tested via Mann-Whitney U test. * p<0.05, ** p<0.01, *** p<0.001.*

Appendix C: Significance of Travel Time change for Small Trunk Service Lines, 2023-2025.

Timeslot	Median 2023	Median 2025	Change	% change	p-value	Sig.
AM peak	5.15	4.33	-0.82	-15.9%	<0.001	***
PM peak	5.07	4.02	-1.05	-20.7%	<0.001	***
Night	5.18	3.20	-1.98	-38.3%	<0.001	***

*Significance tested via Mann-Whitney U test. * p<0.05, ** p<0.01, *** p<0.001.*

Appendix D. Significance of Operational Speed change for Trunk Service Lines, 2023-2025.

Timeslot	Median 2023	Median 2025	Change	% change	p-value	Sig.
AM peak	8.75	10.11	1.37	15.6%	<0.001	***

PM peak	7.26	9.82	2.56	35.2%	<0.001	***
Night	8.04	11.45	3.41	42.4%	<0.001	***

*Significance tested via Mann-Whitney U test. * p<0.05, ** p<0.01, *** p<0.001.*

Appendix E. Significance of Operational Speed change for Small Trunk Service Lines, 2023-2025.

Timeslot	Median 2023	Median 2025	Change	% change	p-value	Sig.
AM peak	5.47	2.44	-3.02	-55.3%	<0.001	***
PM peak	5.76	3.00	-2.76	-47.9%	<0.001	***
Night	3.72	5.50	1.78	47.8%	0.0000	***

*Significance tested via Mann-Whitney U test. * p<0.05, ** p<0.01, *** p<0.001.*