The Impact of Articulated Buses: A Mixed-Methods Approach

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The Impact of Articulated Buses: A Mixed-Methods Approach

by

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Preface

This thesis marks the completion of the Master's programme in Transport, Infrastructure and Logistics at Delft University of Technology. The research was conducted in collaboration with RET, the public transport operator in the Rotterdam region, and focuses on the deployment of articulated buses as a response to increasing crowding levels on specific bus lines.

The topic appealed to me due to its strong relevance to contemporary urban mobility challenges, as well as the opportunity to apply data analysis and modelling techniques to a practical case within a complex operational environment.

I would like to express my sincere gratitude to my university supervisors, Dr. Ir. N. van Oort and Dr. J.A. Annema, for their invaluable guidance, critical feedback, and continuous support throughout this process. Their supervision not only made the thesis an instructive experience, but also an enjoyable one. I especially appreciated their availability and the engaging meetings we had.

Furthermore, I would like to thank all RET staff who contributed to this research, in particular M. Brouwer, for their time, valuable insights during interviews, and support in providing essential data.

Finally, I am deeply grateful to my family and friends for their unwavering support, encouragement, and patience during the completion of this thesis.

Job van Witsen
Delft, July 2025

Summary

This thesis investigates the impacts of deploying articulated buses in urban public transport networks facing capacity constraints and labour shortages. As public transport operators struggle to maintain service quality amid increasing demand and a declining availability of bus drivers, articulated buses offer a promising solution by providing higher vehicle capacity without increasing the number of trips. While widely used in practice, their broader implications for service quality, crowding, and ridership remain underexplored in academic literature. To address this gap, the central research question guiding this study is: *"What are the impacts of the deployment of articulated buses?"* The analysis focuses on how articulated buses affect operational performance and passenger experience, providing insights into their potential role in sustaining and enhancing the quality of urban bus services.

Methodology

To address the main research question, this thesis follows a structured methodology comprising four successive phases. The first phase entails a comprehensive analysis of crowding in public transport, based on academic literature and expert interviews, aiming to identify key challenges, establish relevant performance indicators, and evaluate the potential of articulated buses as a response to capacity issues. In the second phase, a consideration framework for the deployment of articulated buses is developed, informed by interviews with representatives from peer transport operators that explore their decision-making processes, expected benefits, and practical challenges. The third phase introduces a case study of Rotterdam, in which Automated Fare Collection (AFC) data is analysed for bus lines experiencing high levels of crowding. To assess service performance, crowding levels are categorised using the Transit Capacity and Quality of Service Manual (TCQSM) through Level of Service (LoS) ratings. The final phase consists of simulations using the OV-Lite model within the OmniTRANS simulation environment, designed to evaluate the effects of deploying articulated buses on ridership, including the impact of reduced service frequency and improved comfort due to increased capacity. Figure 1 schematically presents the overall methodology.

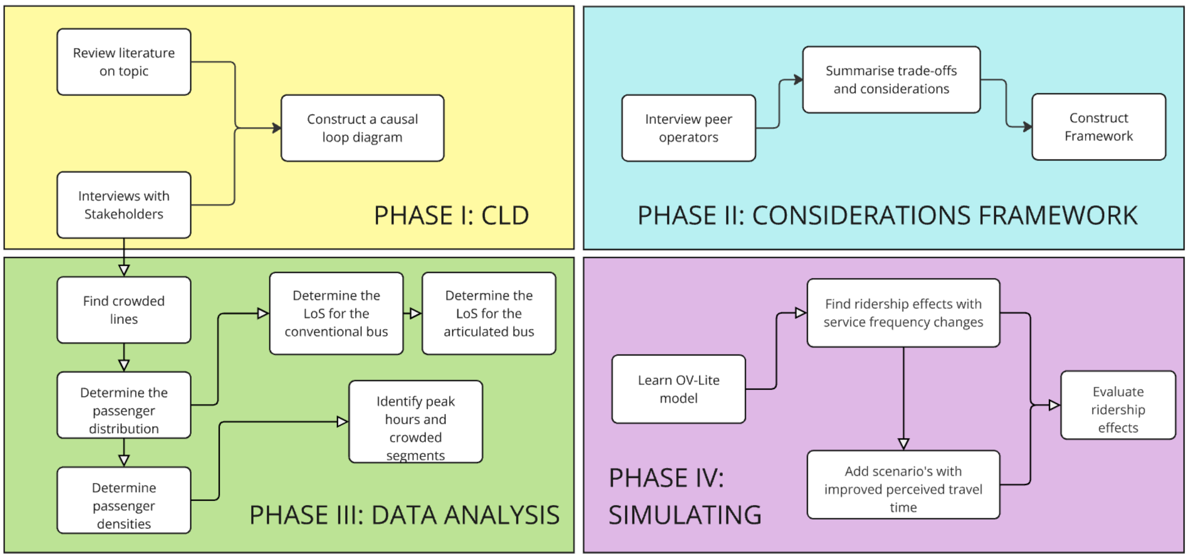

Figure 1: Flowchart of the Research Methodology

Causal Loop Diagram (CLD)

Crowding in bus networks has substantial negative effects on both passenger experience and operational performance, ultimately lowering the overall QoS. Crowding leads to longer dwell times, reduced on-time performance, denied boardings, and increased perceived travel time, which in turn discourage ridership. It also contributes to a less friendly environment for drivers, increasing absenteeism and staff turnover, further reducing service availability. Additionally, crowding undermines perceived safety and facilitates fare evasion, especially in poorly monitored vehicles. The proposed deployment of articulated buses is expected to relieve crowding and improve comfort and reliability, but may also reduce network flexibility and, when combined with lower frequency, potentially increasing waiting times.

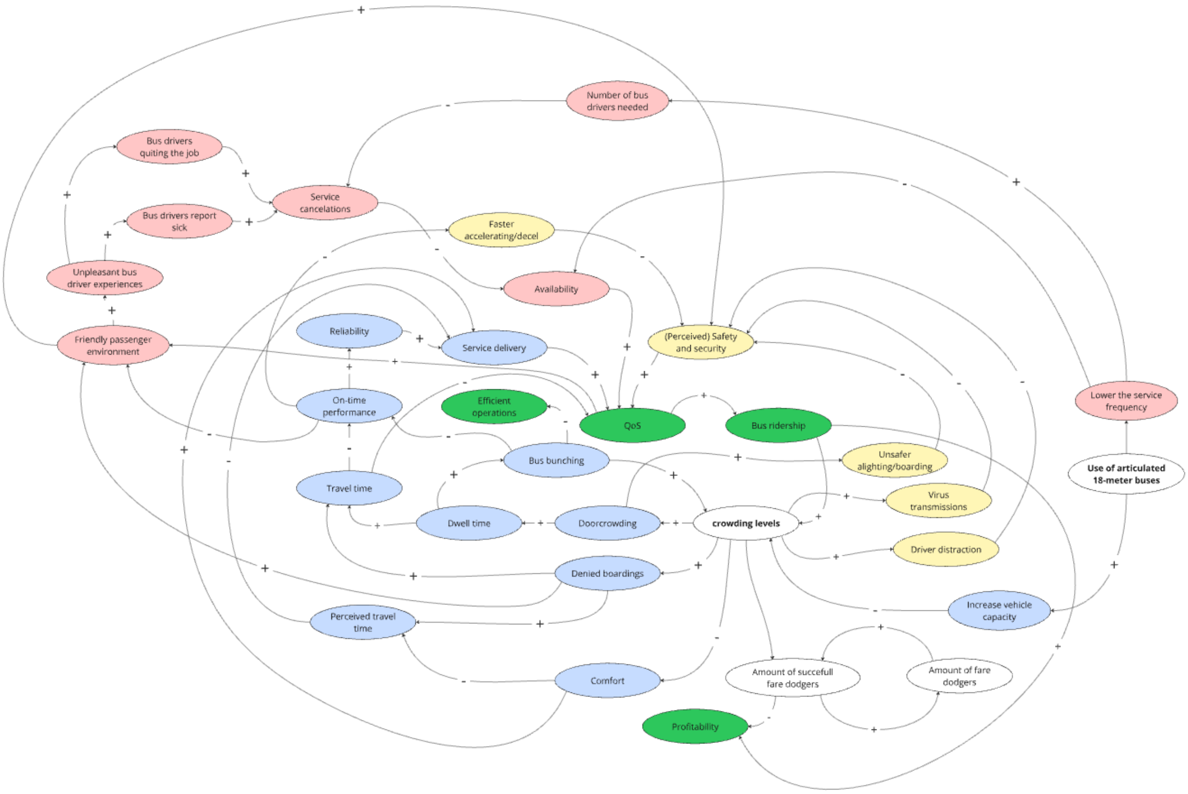

Figure 2: Complete CLD illustrating the relationships between factors influencing the QoS and the challenges faced by RET, along with the proposed solution.

Consideration Framework

A consideration framework for the deployment of articulated buses was developed based on insights from interviews with HTM and GVB, two Dutch public transport operators with practical experience in operating the high-capacity vehicles. Articulated buses are primarily introduced to address excess passenger demand when increasing service frequency is not feasible due to staff shortages or operational inefficiencies. Key trade-offs and considerations identified include reduced network flexibility, limitations of mixed fleets, and the need for stop adjustments or charging infrastructure, particularly when deploying electric buses. Despite these challenges, both operators report smooth implementation processes, minimal driver resistance, and benefits such as the elimination of reinforcement trips and improved QoS in the network. The framework (Figure 3) highlights operational, infrastructural, and organisational factors that transport operators should weigh when evaluating the suitability of articulated buses for their networks.

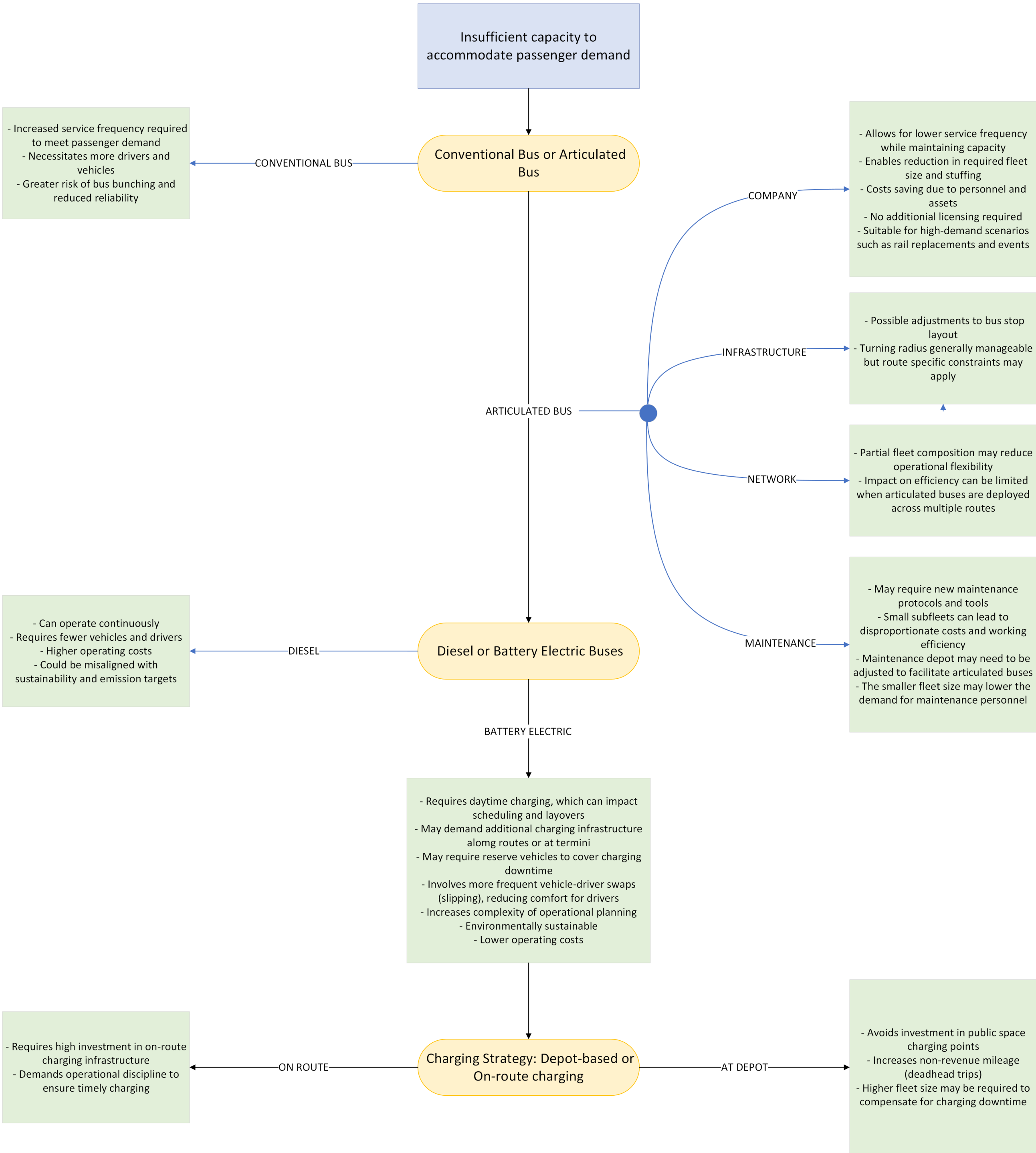

Figure 3: Consideration framework for the deployment of articulated buses

Data-Analysis

A data-analysis on the network of Rotterdam is performed. Using AFC data, crowding levels were analysed for selected high-demand bus lines (32, 33, 668 and 70) and converted to a level of service (LoS) via tresholds of the TCQSM manual. The results showed that multiple lines experienced frequent overcrowding during peak periods, with LoS categories E and F indicating substantial passenger discomfort. Overcrowding was typically concentrated on specific segments of the route, particularly near major hubs or schools, highlighting the uneven distribution of capacity pressure. These insights provided a detailed understanding of where and when crowding occurs and formed the empirical foundation for assessing the potential impact of articulated buses.

Table 1 presents the LoS distribution for line 70 (inbound direction), comparing current conditions using standard buses with simulated conditions using articulated buses. The data show substantial improvements across all periods. For example, during the morning peak, the share of stop-segments rated as LoS A increased from 69.6% to 91.5%, while LoS E and F conditions nearly disappeared. Similar improvements are visible during all other periods of the day, confirming that deploying articulated buses can significantly reduce crowding and enhance service comfort, even without increasing frequency.

Table 1: Percentage distribution of LoS by period for Line 70 (Inbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	69.6	15.1	6.8	4.8	1.2	**2.5**	91.5	6.0	1.4	0.6	0.4	**0.0**
Midday (09:00–15:30)	60.2	20.3	12.4	4.3	**1.7**	**1.0**	92.9	6.1	1.0	0.0	**0.0**	**0.0**
Evening peak (15:30–18:30)	84.7	7.1	3.2	2.7	**1.1**	**1.1**	95.0	3.9	0.9	0.2	**0.0**	**0.0**
Evening (18:30–01:00)	93.7	2.8	3.2	0.4	0.0	0.0	99.6	0.4	0.0	0.0	0.0	0.0

Ridership Simulations

With the OV-Lite model which runs on OmniTRANS software effect on ridership were explored. The simulation results show that ridership is sensitive to changes in service frequency, particularly during peak hours. Reducing the number of buses per hour leads to a notable decline in passenger numbers. For instance, Line 70 loses approximately 15 percent of its ridership for each vehicle removed during the morning peak. Introducing articulated buses improves the quality of service by increasing capacity and reducing crowding. These benefits were modelled through the reductions in perceived travel time as a proxy for the comfort gain. A reduction of around 20 percent was generally sufficient to recover baseline ridership when frequency was lowered by one bus per hour. However, when frequency was reduced by two buses, this effect was usually not strong enough to fully restore passenger levels. Although full recovery was not achieved, the improved perceived travel time still helped to mitigate the impact of service reductions on ridership.

During the midday period, when service frequency was increased, ridership rose across all lines. The most significant increases were observed on lines 70 and 32. These lines serve major transfer points in the network and connect densely populated areas with the city centre. Line 70 showed the strongest growth, gaining over 1,300 additional passengers when frequency increased from six to eight buses per hour. Line 32 also demonstrated high elasticity. When comfort improvements were introduced alongside frequency increases, ridership gains became even more pronounced. These findings suggest that deploying articulated buses can help boost midday ridership and mitigate the negative effects of lower service frequency during peak periods.

Conclusion

This thesis examined the impacts of deploying articulated buses on both operational performance and passenger experience. Crowding was identified as a central issue affecting nearly all elements of the overall QoS, including aspects as comfort, reliability, and perceived travel time. The CLD demonstrated how crowding can lead to reinforcing negative feedback loops, such as bus bunching and increasing pressure on bus drivers, ultimately reducing operational efficiency, passenger- and driver satisfaction.

AFC data analysis revealed that articulated buses can substantially improve the LoS regarding crowding. When comparing 12-meter and 18-meter configurations, higher LoS levels became significantly more frequent under the articulated scenario, indicating improved conditions for passengers.

To better understand behavioural responses, ridership simulations were conducted using the OV-Lite model. These showed that while a reduction in frequency may negatively affect ridership, this loss can be mitigated or offset if perceived travel time improves. A 20% reduction in perceived travel time was generally sufficient to compensate for one fewer bus per hour. Off-peak improvements in ridership were also observed when deploying articulated vehicles with higher comfort levels.

Operational and infrastructural considerations are crucial. While articulated buses offer more capacity, they reduce fleet flexibility and may require route-specific infrastructure adjustments. In particular, battery-electric models introduce constraints related to charging infrastructure and downtime. Despite these challenges, peer operators reported relatively smooth transitions and positive effects on service alignment with demand.

Discussion

There are several limitations to this study. The constructed CLD clarifies relationships between key variables but does not provide insight into the magnitude of the impacts of crowding on operations. Additionally, the AFC data does not capture denied boardings, which limits its ability to fully represent the capacity shortfall. The data is also limited to one week, restricting the generalisability of the findings.

For the simulation part, it was assumed that passengers would immediately recognize the benefits of improved service, without considering the time needed for behavioral adjustments. Moreover, the model did not distinguish between captive and non-captive passengers, neglecting important behavioral differences.

The study was conducted in the context of growing capacity issues at RET, combined with a persistent shortage of bus drivers. Deploying articulated buses seems to be a promising solution for alleviating crowding without requiring additional staff. However, this solution should not be seen as universal; other measures might be more effective in certain cases.

Recommendations

To strengthen the reliability, depth, and practical applicability of this study, several recommendations are proposed across four key areas: system modelling, data integration, simulation refinement, and cost framework development.

First, the current CLD effectively illustrates key relationships influencing QoS, ridership, and operational dynamics, yet it lacks quantification. Incorporating numerical weights or elasticity values based on empirical data or expert input is recommended to better reflect system behaviour and prioritise interventions.

Second, the considerations framework could be enhanced by integrating financial estimates for capital and operational investments, such as vehicle procurement, infrastructure upgrades, and maintenance costs. This would enable cost-benefit analyses and promote transparent trade-off discussions. The financial impact of these considerations is highly context-dependent and influenced by factors such as existing depot infrastructure or bus bay dimensions.

Third, improvements to the data analysis approach are advised. The integration of APCs would improve ridership accuracy by accounting for OV-Pay users and fare evaders. Additionally, including denied boardings and combining quantitative data with passenger surveys would yield a more comprehensive understanding of both actual and perceived crowding.

Finally, the ridership simulations could be refined in multiple ways. Synchronising origin-destination data would improve internal consistency, and validating simulation outcomes with real-world deployment data would enhance the reliability of the simulations. Moreover, the current model assumes immediate behavioural adaptation, whereas incorporating time-dependent ridership evolution would offer a more realistic view of passenger response. Network-wide impacts should also be examined, including effects on adjacent lines and total passenger-kilometres. Furthermore, it is recommended to adopt an iterative passenger assignment method that accounts for in-vehicle crowding levels, as this could significantly improve the model's sensitivity to perceived service quality.

Recommendations for the RET

Based on the analysis, it is recommended that RET prioritise the deployment of articulated buses. Line 70 stands out as the most problematic, consistently experiencing overcrowding and reaching level F during nearly all time periods in both directions. It is therefore advised to deploy articulated buses on this line as the first step.

Line 68 is also a logical candidate for the deployment of articulated buses, as it frequently experiences overcrowding, likely due to high demand from secondary school pupils. However, the directional demand imbalance should be considered, as high demand in one direction leads to overcapacity in the other.

Line 32 also shows signs of crowding, although to a lesser extent. As it serves the city centre and attracts passengers across its entire length, the buses are consistently well-occupied. Given the efforts to promote car-free urban areas and the potential for ridership growth, deploying articulated buses on this line in the future is advisable.

For Line 33, no significant crowding issues were observed, so the deployment of articulated buses on this line is not recommended.

Additionally, it is recommended that RET engage in discussions with the concession authority regarding the current obligation to operate a fixed number of service kilometres. This requirement limits the operator's ability to respond flexibly to staff shortages and evolving travel demand. If this obligation remains, increasing frequency during the midday period on Lines 32 and 70 is suggested, as these lines serve densely populated residential areas, city centres, and major transfer nodes, and maintain high ridership throughout the day.

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1 Introduction

Public transport (PT) is a vital backbone of sustainable urban development, facilitating efficient movement across cities. Urban PT typically consists of three key modes: metro, tram, and bus. The metro connects major urban areas and suburbs, offering high capacity and rapid transit. The tram network provides more localised service, linking neighbourhoods to key commercial and residential areas. The bus system extends the reach of the network, serving both urban and rural regions. However, despite its importance, many public transport systems face significant challenges in maintaining a high quality of service (QoS) (Ibarra-Rojas et al., 2015).

Failing to uphold a high quality of service can have serious consequences for public transport operators. Bar-Yosef et al. (2013) show that as the perceived quality of service declines, public transport lines tend to lose non-captive passengers. Non-captive passengers are those who have access to alternative modes of transport and choose public transport only when it meets their quality expectations. In contrast, captive users rely on public transport due to the absence of viable alternatives. Over time, a decline in quality of service can trigger a vicious cycle in which ridership continues to fall, eventually leaving only captive users on the line.

Maintaining and enhancing the quality of service in public transport is therefore essential for encouraging a modal shift from private vehicles to public transit. Increased use of public transport contributes not only to environmental sustainability through lower emissions, but also helps to reduce traffic congestion, improve urban accessibility, and lower the societal costs associated with car dependency. For this reason, investment in high quality public transport systems is a critical component of sustainable urban mobility strategies.

Public transport operators aim to maximise ridership while ensuring a high quality of service. Although the concept of quality of service is broad and loosely defined, as it covers various aspects of the passenger experience, numerous studies have identified several consistently important factors. When focusing specifically on the bus as a mode of public transport, the literature (as further discussed in the literature review section) highlights comfort, travel time, and crowding as key determinants of perceived service quality (Cascajo & Monzon, 2014; dell'Olio et al., 2011). These factors are therefore influential in shaping individuals' mode choice.

A core task for operators is to ensure sufficient capacity to provide passengers with a comfortable and reliable journey. If a service line is overcrowded, or in other words, if the available capacity does not meet passenger demand, one option is to increase service frequency. Increasing frequency, however, requires additional vehicles and drivers. This is problematic in the current context, as one of the most pressing challenges facing European bus networks is the growing shortage of qualified drivers. This issue is particularly acute in the Netherlands, where 20 percent of all bus driver vacancies remained unfilled in 2024. The shortage is expected to worsen, potentially doubling by 2028 due to an ageing workforce and limited inflow of new drivers (Algemeen Dagblad, 2024; Mobiliteit.nl, 2024).

Labour shortages significantly constrain operators' ability to deliver frequent services. In many cases, they are forced to reduce frequency or cancel trips altogether, which results in increased crowding, longer waiting times, denied boardings, and lower punctuality. These developments undermine the quality of service and may further discourage passengers from using public transport (Baharum & Haron, 2020).

An alternative approach to increasing frequency is to increase vehicle capacity. This can be achieved by deploying larger buses, which allows more passengers to be transported without increasing the number of trips. In some cases, frequency may even be slightly reduced without compromising overall capacity. This approach has the advantage of requiring fewer drivers, which can help address the labour shortage while maintaining or even improving service quality on overcrowded lines.

1.1. Scientific Gap

Extensive research has been conducted on public transport and the factors influencing mode choice. However, the role of articulated buses as part of capacity and quality improvement strategies remains underexplored. Most existing studies on articulated buses focus primarily on technical and operational aspects of vehicle dynamics. Only limited research has been found that addresses their potential impact on travel time and dwell time, and virtually none investigates their broader implications for both operators and passengers within conventional bus networks.

This thesis aims to address this gap by exploring the potential impacts of deploying articulated buses, considering both operator outcomes and passenger experience.

1.1.1. Research Questions

To address this knowledge gap, the central objective of this thesis is to answer the following main research question:

"What are the impacts of the deployment of articulated buses?"

This question is supported by the following subquestions:

- *How does crowding affect bus operations from both the passenger and operator perspective?*
- *What could be the consideration framework for the deployment of articulated buses?*
- *What is the current Level of Service on crowding and how could the use of articulated buses enhance this level?*
- *What is the expected impact on ridership when articulated buses are introduced into the network?*

1.2. The RET

The Rotterdamsche Elektrische Tram (RET), the public transport operator in Rotterdam, serves approximately 150 million passengers annually (MRDH, 2023), and forms the case study for this research. Within the RET network, the metro functions as the primary mode of transport, connecting the city centre with surrounding suburban and periurban areas. Its high capacity and relatively high speed make it the preferred option for many travellers. The tram network provides local accessibility within the city, while buses offer complementary coverage, both within the urban area and towards peripheral or rural destinations. Although the metro accommodates the majority of passenger flows, the bus and tram networks fulfil a crucial supporting function by ensuring first and last mile connectivity.

Despite the dominant role of the metro, certain bus lines continue to face capacity challenges. This is particularly the case on lines that serve educational institutions and carry large volumes of school pupils during peak periods. Given the role of the bus in first and last mile transport, these crowding issues are usually limited to specific sections of the route rather than affecting the entire service.

Simultaneously, the RET is confronted with a shortage of qualified bus drivers, a challenge that affects many public transport operators across Europe. In response to this situation, the RET is currently considering the procurement of articulated buses. At present, the RET operates a fleet of 266 buses (RET, n.d.), a significant portion of which is not yet electrified. As fleet electrification becomes increasingly mandatory, transitioning to articulated vehicles now presents a strategic opportunity to combine capacity enhancement with the fleet modernisation.

Articulated buses have a total length of eighteen metres, making them six metres longer than standard twelve metre vehicles. This increased length allows for approximately fifty percent more seating capacity and additional standing room, thereby offering a practical solution to mitigate crowding without increasing service frequency.

1.3. Scope

This thesis focuses on the potential impacts of articulated buses on both the public transport operator and the passenger. Although various strategies exist to address capacity issues, this study exclusively examines the potential of articulated buses.

The thesis provides insight into factors that influence mode choice. However, no stated preference study is conducted. Passenger perception and willingness to use articulated buses are therefore not directly assessed. Instead, relevant insights are derived from existing literature.

To evaluate service quality, this research places emphasis on crowding. While many factors contribute to perceived quality, such as punctuality, comfort and reliability, this thesis highlights crowding as the primary focus. A causal loop diagram is constructed to illustrate how crowding may influence and interact with other dimensions of service quality.

1.4. Relevance

In a society where environmental challenges such as congestion and global warming are becoming increasingly prominent, there is a growing need to move towards more sustainable modes of transport. At the same time, PT operators are facing increasing difficulties in maintaining a high QoS while striving to maximise ridership. This not only threatens public perception of bus services, but potentially of the PT system as a whole. To encourage a modal shift towards public transport, it is essential to maintain a high level of service quality.

This thesis aims to contribute to both scientific knowledge and practical application by providing insights into the potential role of articulated buses in addressing capacity issues. It addresses an existing gap in academic literature and evaluates whether articulated buses could present a viable solution to capacity challenges in urban bus networks.

1.5. Outline of the Report

The structure of this thesis is organised as follows. Chapter 2 presents the methodology applied to address the main research question and its associated sub-questions. Chapter 3 provides the literature review, focusing on two central themes: first, an overview of existing research on articulated buses, and second, an examination of the factors that influence individuals' mode choice with respect to bus transport. Chapter 4 presents the background analysis, where a Causal Loop Diagram (CLD) is used to visualise the effects of crowding on service quality, as well as the potential impact of articulated buses in alleviating these effects. Chapter 5 introduces an consideration framework for the deployment of articulated buses, developed based on interviews with peer operators who have practical experience with articulated bus operations. Chapter 6 introduces the case study of RET. Through data analysis of highly crowded lines in the RET network, this chapter investigates the severity, location, and timing of capacity issues, and explores how the level of service changes when articulated buses are deployed instead of conventional buses. Chapter 7 assesses the impact of articulated buses and service frequency changes on ridership. This analysis makes use of the OmniTRANS software and the OV-Lite model, in which comfort effects are incorporated by adjusting the speed factor to account for crowding. Chapter 8 concludes the thesis by summarising the key findings and answering the main research question. Finally, Chapter 9 provides recommendations and a critical discussion, including a reflection on the limitations and broader implications of the study.

2 Methodology

To address the main research question, this thesis adopts a structured methodology comprising four distinct phases.

The first phase involves a comprehensive background analysis, combining insights from academic literature and expert interviews to examine the effects of crowding in public transport. This phase aims to identify key issues, establish relevant performance indicators, and assess the potential impact of introducing articulated buses as a response to capacity challenges.

The second phase focuses on the development of an consideration framework for the deployment of articulated buses. To construct this framework, interviews with representatives from peer transport operators are conducted. These interviews explore the decision-making processes surrounding the introduction of articulated buses and identify both the anticipated benefits and encountered challenges. The findings are then systematically integrated into the framework.

In the third phase, the case study of Rotterdam is introduced. This phase centres on the analysis of Automated Fare Collection (AFC) data for bus lines previously identified as experiencing high levels of crowding. Additionally, the Transit Capacity and Quality of Service Manual (TCQSM) is employed to assign a Level of Service (LoS) to observed crowding levels, providing a standardised and comparable metric for service evaluation.

The final phase, the modelling phase, assesses the potential impacts of deploying articulated buses on ridership. This includes evaluating the effects of reducing service frequency and the improvements in comfort resulting from increased capacity and reduced crowding. For this analysis, the OV-Lite model is utilised within the OmniTRANS simulation environment.

Table 2.1 gives an overview over the used methods and the associated research questions.

Table 2.1: Summary of Research Methodology

Main Research Question: *What are the impacts of the deployment of articulated buses?*

Sub-Research Question	Methodology
1. How does crowding affect bus operations from both the passenger and operator perspective?	Review relevant literature and conduct in-depth interviews with stakeholders at RET. Summarise findings in a causal loop diagram to find relations.
2. What could be the consideration framework for the deployment of articulated buses?	Consult peer transit operators and conduct interviews to identify consideration criteria and trade-offs associated with deploying articulated buses.
3. What is the current Level of Service on crowding and how could the use of articulated buses enhance this level?	Analyse AFC data using Python to determine current passenger loads. Evaluate Level of Service based on TCQSM standards and reassess after adjusting capacity for articulated buses.
4. What is the expected impact on ridership when articulated buses are introduced into the network?	Use the OV-Lite simulation model to assess changes in ridership resulting from improved service frequency and improved perceived travel time (as proxy from comfort gain) due to the deployment of articulated buses.

2.1. The impact of Crowding

The first phase of this project is related to find the impacts of crowding. This phase focuses on answering the following subquestion:

1. *How does crowding affect operations from both a passenger and operator perspective?*

To effectively address these questions, it is essential to develop a thorough understanding of the problem. In this phase three primary methods will be conducted: Literature review, interviews and constructing a Causal Loop Diagram (CLD).

2.1.1. Literature review

In order to gain a better understanding of the problem of crowding in buses, literature on this topic was reviewed. The literature is primarily focused on factors influencing the decision to use the bus and on how crowding can affect these factors. The primary databases used for this literature search are Google Scholar and Scopus.

Concept Group	Details
Key Factors	**Keywords:** Urban Bus, Modal Share **Search Strategy:** Keywords combined using AND
Perceived Satisfaction	**Keywords:** Level of Service (LoS), Acceptance, Factors **Search Strategy:** Factors AND (Acceptance OR Satisfaction)
Level of Service (LoS)	**Keywords:** Reliability, Crowding, Passenger Experience **Search Strategy:** Keywords combined using AND
Articulated Buses	**Keywords:** Performance, Capacity, Efficiency **Search Strategy:** Keywords combined using AND

Table 2.2: Keywords and Search Strategies

For Google Scholar, search terms will primarily include queries such as: *"Which factors affect the modal share of buses/public transport?"* or *"The influence of articulated buses on network performance."*

2.1.2. Interview with Stakeholders

To gain a comprehensive understanding of the problem, a series of semi-structured interviews will be conducted with key stakeholders within the RET. These stakeholders include the asset manager, the maintenance manager, operational staff, and representatives from both the strategic and development departments.

Interview Questions

The following questions will serve as a guide during the interviews:

- What problems does RET currently experience with the use of traditional 12-metre buses?
- Which stakeholders are most affected by these problems?
- What do you perceive to be the short-term and long-term impacts of these issues?
- Are there specific locations or time periods during which the problems are most prominent?
- Is there any quantified data available that illustrates the extent of the problem?
- Why do you believe that the deployment of 18-metre buses could offer a solution? Would this also be viable in the long term?
- Have alternative solutions been considered? If so, why were these ultimately not pursued?

The outcomes of the interviews will subsequently be analysed, with specific attention given to insights regarding the impact of crowded bus lines on the operations of the public transport provider.

2.1.3. Causal Loop Diagram

Constructing a causal diagram is an approach used to visualize the relationships between various factors, enabling the identification of causal connections (Forrester, 1997). It provides a structured overview of how different elements interact and influence one another, making it an effective tool for understanding the potential impact of a proposed solution, particularly in cases where effects become visible over an extended period (Wlisses B. Fontoura & Ribeiro, 2024). The constructed diagram incorporates insights from both the literature review and interviews with stakeholders.

2.2. Consideration Framework

In the second phase of this research an consideration framework is constructed which gives insights in the decsion making processes when deploying articulated buses. RET is one of the few, if not the only, public transport providers in the Netherlands that does not operate articulated buses. This unique position offers an opportunity to gain valuable insights by conducting interviews with bus operators from other regions and municipalities that have already undergone a fleet transition. These interviews can shed light on their experiences, focusing on both the benefits and the challenges encountered during the implementation of articulated buses.

Interviewed operators include:

1. HTM (The Hague): Interviewed a professional from the 'Reizigers' (Passenger Services) department. This department focuses on customer experience and service planning.
2. GVB (Amsterdam): Interviewed a professional from the Transport Development department.

HTM is an operator which is currently in the transition to articulated buses. They have recently made all the decsionsns. GVB is an operator which already make use of articulated buses for a long time. This study makes use of semi-structured to non structured interviews.

The following key questions were used to guide the interviews:

- What were the main reasons for acquiring articulated buses?
- Which challenges arose during the transition process?
- What were the observed effects on the network and daily operations?
- What was the impact on maintenance processes and depot facilities?
- Which trade-offs emerged in relation to the deployment of electric articulated buses?

To interpret the interviews, the answers were analysed thematically and compared across the two operators. Recurring patterns and notable differences were identified to highlight shared challenges and context-specific considerations. These findings were then incorporated into the construction of the consideration framework and served to enrich the understanding of relevant operational and organisational factors.

2.3. The data-analysis phase

After the background phase the second phase, the data analysis starts. This phase centers around the following two subquestions:

3. *What is the current Level of Service on crowding and how could the use of articulated buses enhance this level?*

AFC data involves much data as it registers all the transaction of all the passengers in the network. Given the extensive data available, only lines which are marked as crowded will be taken further for analysis. In this data analysis the goal is to indicate where on the lines it is crowded and how the passengers are distributed over the day. After this step the analysed lines will be eventually assessed based on thresholds from the TCQSM manual. This assessing will be limited to crowding levels.

Based on the AFC data, the analysis focuses on the selected crowded lines within the RET bus network. The primary objective is to examine the passenger distribution along these lines and to assess how the deployment of 18-metre buses, as an alternative to the current 12-metre buses improves service quality. To assess crowding levels, the number of passengers per square metre is used as an indicator, following the approach of Li and Hensher (2013a). While this metric does not fully capture passengers' subjective perception of comfort, it provides a suitable and objective proxy for identifying locations and time periods with a high crowding potential. Due to the absence of survey data, psychological aspects of crowding cannot be directly incorporated in this analysis.

2.3.1. The data set

The data used for this analysis consists of Automated Fare Collection (AFC) data. The dataset covers week 45 of 2023 (6 November – 12 November). This specific week was selected because OV-Pay (a payment method allowing passengers to travel using debit or credit cards) had only recently been introduced. Since AFC data does not register OV-Pay transactions, it was preferable to use a dataset in which the adoption of OV-Pay was still limited.

Given these circumstances, several corrections need to be applied to the dataset. These include adjustments for passenger growth, fare evasion, and a small correction to account for the share of passengers who already made use of OV-Pay during this period.

2.3.2. Passenger Density Index

The estimation of passenger density for public bus services involves analyzing both onboard crowdedness and station occupancy. Research by Zhang et al. (2014) showed that the Passenger Density Index in a Bus (PDB) serves as the fundamental measurement for evaluating crowding levels in a bus. Their research demonstrated that these indices can be extended over different bus service numbers, stations, and time periods. The key indices are:

- $\rho_B(m)$ — the density of a vehicle assigned to bus service number m.
- $\rho_B(p)$ — the average density of vehicles operating on the line during period p.
- $\rho_B(n)$ — the density of the vehicle at station n.

Symbol	Content
ρ_B	Passengers Density Index in a Bus (PDB).
ρ_S	Passengers Density Index at a Station (PDS).
m	Bus Service Number m of a line.
n	Bus Station n of a line.
$N(m,n)$	The number of the passengers in the vehicle which Bus Service Number is m between Station $n-1$ and Station n.
$O(m,n)$	The number of passengers who get off the vehicle which Bus Service Number is m at the Station n.
$F(m,n)$	The number of passengers who get on the vehicle which Bus Service Number is m at the Station n.
ρ	Different periods in a day.
S_m	The set of all stations that Bus Service Number m pass through.
$\|S_m\|$	The number of stations in the collection S_m.
$B(p)$	The number of bus services which serve in period p of a day.
$B(n)$	The number of bus services which pass through station n in a day.
L	The vehicle load value.
C	The station capacity.

Table 2.3: Definition of Symbols

These indices are computed using the following equations:

$$\rho_B(m) = \frac{\sum_{n \in S_m} N(m,n)}{L \cdot |S_m|} \tag{2.1}$$

$$\rho_B(p) = \frac{\sum_{m \in p} \rho_B(m)}{B(p)} \tag{2.2}$$

$N(m,n)$ is calculated as follows:

$$N(m,n) = \sum_{i=1}^{n-1} (F(m,i) - O(m,i)) \tag{2.3}$$

Table 2.3 provides an overview of the meaning of the symbols.

2.3.3. Calculation of LoS Share

The share of each Level of Service (LoS) category is determined by analyzing the occupancy levels of the bus over the selected route. For each segment between two consecutive stops, the occupancy level is converted into a LoS category using the classification criteria shown in Table **??**. This calculation is repeated for every segment of every trip.

The share of each LoS category within a specific hour is calculated by dividing the count of each category by the total number of segments analyzed for that hour. This calculation is given by:

$$\text{LoS Share} = \frac{\text{Number of segments classified as LoS } X}{\text{Total number of segments analyzed for the hour}} \times 100\% \tag{2.4}$$

Where:

- X represents the LoS category being analyzed (A, B, C, D, E, or F).

The calculated LoS shares are then visualized as pie charts, where each chart represents the distribution of LoS categories for a specific hour. These charts are generated for both Inbound and Outbound trips to facilitate comparison.

2.4. OmniTRANS Simulations

The simulation phase centers around the following sub questions: *What is the effect on bus ridership when deploying articulated buses in the network?*

To assess the potential effects on ridership of deploying 18-meter articulated buses, a transport demand model developed within the OmniTRANS platform is used. OmniTRANS is a transport modelling environment that enables multimodal analyses of travel behaviour and network performance. It allows for scenario testing and impact consideration of infrastructural and policy interventions across various transport modes, including private vehicles, public transport, cycling, and freight.

Within this modelling environment, two relevant models are available to evaluate the impact of changes in public transport characteristics on ridership: the V-MRDH model and the OV-Lite model.

The V-MRDH (Verkeersmodel Metropoolregio Rotterdam Den Haag) is a detailed regional multimodal transport model covering the greater Rotterdam–The Hague metropolitan area. It incorporates socio-demographic data, spatial developments, and multimodal transport networks to simulate and forecast travel demand. The model is typically used for strategic transport planning, evaluating infrastructure projects, and long-term policy analysis.

The OV-Lite model, on the other hand, is a simplified transport model designed specifically for public transport analyses. It provides a more lightweight alternative to the V-MRDH, focusing solely on public transport ridership and network effects. While it lacks the multimodal integration of the V-MRDH model, it allows for more efficient computation and rapid scenario testing, particularly when only public transport-related interventions are of interest.

Given the focus of this thesis on public transport and the practical constraints regarding computational capacity and access, the OV-Lite model was selected as the most appropriate tool for analysing the effects of articulated bus deployment.

2.4.1. Ridership Effects

The OV-Lite model is based on an elasticity approach, meaning that changes in ridership are estimated based on changes in travel time. In this framework, an increase in travel time by *x* minutes is expected to result in a decrease in ridership by *y* percent, depending on the elasticity applied. Since the model uses elasticities to simulate behavioural responses, all effects on service attractiveness must ultimately be expressed in terms of perceived travel time. Therefore the perceived travel time will serve as a proxy for the comfort gain as a result of a enhanced vehicle capacity.

To influence perceived travel time, a speed factor can be applied. For example, a speed factor of 1.1 implies that passengers perceive the journey as 10% faster than it actually is, leading to a relative reduction in perceived travel time and, as a result, a positive effect on ridership. Importantly, this adjustment only affects perceived travel time; it does not alter the scheduled or actual travel times within the model.

It is worth noting that the OV-Lite model developed by Goudappel and TU Delft for HTM includes an additional feature: a capacity constraint whereby crowding reduces the perceived attractiveness of the service. This feature is currently unique to HTM's version and is not available in the OV-Lite model used by RET for this analysis.

2.4.2. Scenarios

This simulation analysis is conducted on four public transport lines: 32, 33, 68, and 70, which are the same lines previously examined in the data analysis. The primary objective is to assess the impact of deploying articulated buses on ridership levels. A central assumption is that articulated buses, due to their higher capacity, allow for a reduction in service frequency during peak periods. This reduction is applied to either the morning or evening peak, as these timeframes are typically characterised by high demand and limited driver availability, making operational savings particularly relevant.

Within the current concession framework, the RET operates under agreement with the MRDH, which specifies a fixed number of service kilometres to be delivered. As such, any reduction in frequency during peak hours must be compensated by an increase in frequency during off-peak hours, typically the midday period. This ensures that the total number of service kilometres remains consistent with contractual obligations.

The passenger volumes obtained through the empirical data analysis do not fully align with those produced by the OV-Lite model, indicating a lack of calibration or synchronisation between the two sources. Therefore, this simulation should be considered a shadow analysis. Rather than aiming to predict exact ridership numbers, its purpose is to illustrate potential trends in passenger growth or decline. It also aims to examine whether the comfort-related benefits of articulated buses could offset any negative effects caused by a lower service frequency.

For each time period, the simulation first establishes a baseline scenario that reflects current network characteristics and frequencies. In the adjusted scenarios, frequency reductions are applied in the morning and evening peaks, while frequency increases are introduced in the midday period. To account for the enhanced comfort associated with articulated buses, a perceived travel time adjustment is introduced. Since comfort cannot be directly modelled in the OV-Lite tool, perceived travel time serves as a proxy variable. Specifically, three simulation variants are tested using speed factors of 1.1, 1.2, and 1.3, which represent reductions in perceived travel time of 10%, 20%, and 30%, respectively. These reductions reflect the assumption that passengers perceive the trip as shorter due to improved ride comfort.

2.5. Summarized methodology

Figure 2.1 containts the methodolgy for this thesis schematized per phase.

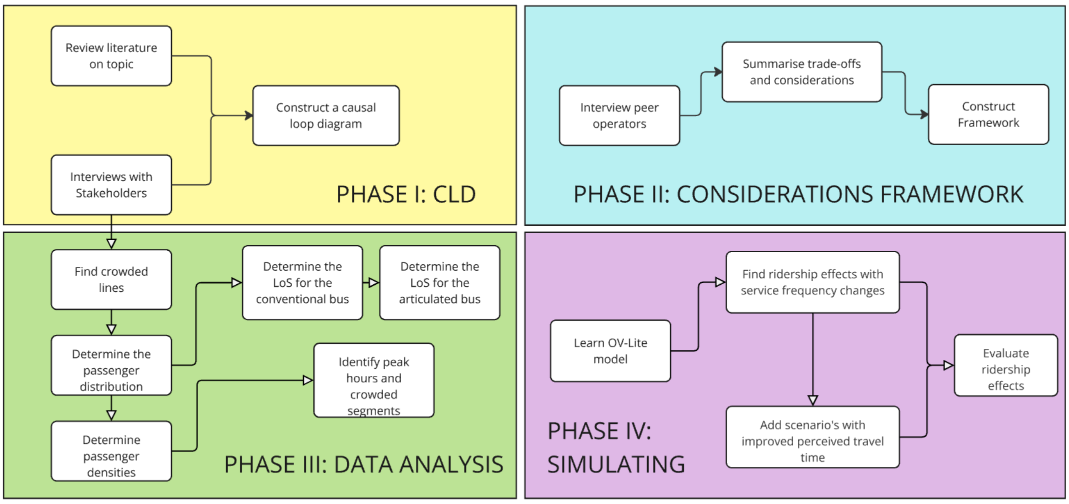


Figure 2.1: Flowchart of the Research Methodology

3
Literature Review

This chapter presents the literature review for this thesis. The review begins by examining existing research on articulated buses. Unfortunately, studies on this topic are rather limited. The available literature primarily focuses on technical and operational aspects of vehicle dynamics.

To gain a broader understanding of the potential impact of articulated buses, the scope of the review will then be expanded. The focus will shift to identifying the key factors that influence bus usage, providing a more comprehensive perspective on the conditions under which articulated buses may be an effective solution.

3.1. Articulated buses

Articulated buses are widely used in Bus Rapid Transit (BRT) networks due to their higher passenger capacity compared to traditional buses. On high-capacity bus routes, articulated buses reduce staff and bus stock necessary to transport passengers (Smith & Hensher, 1998). Their multiple doors enable faster boarding and alighting, improving passenger flow and operational efficiency. Additionally, their flexible articulation joint enhances maneuverability, allowing them to navigate urban corridors effectively. As a result, articulated buses are a key component of many BRT systems (Levinson et al., 2002).

Pahs et al. (2002) emphasized that the use of articulated buses in BRT networks enhances the overall QoS, making public transit a more attractive option for non-captive travelers—those who have alternative transport choices but opt for BRT due to its efficiency and convenience.

El-Geneidy and Vijayakumar (2011) conducted research on the effects of articulated buses on dwell and running times. Their findings indicate that articulated buses can reduce dwell time compared to traditional buses, particularly under high passenger loads. However, the extent of these savings is contingent on the operational strategy of the bus operator. If boarding and alighting are restricted to a single door, the dwell time may actually exceed that of conventional buses, negating potential efficiency gains.

Despite the potential dwell time savings, total running time does not necessarily decrease when using articulated buses. Their larger size results in slower acceleration and deceleration, as well as longer merging times in mixed traffic, which can offset the benefits gained from reduced dwell times.

3.2. Factors of Mode Choice

In order to gain a better understanding about ridership for the bus in an urban network, it is important to get a understanding about the factors which play a role in the decision of the mode. The most common travel modes include walking, cycling, driving, and public transport. In general, the most frequently considered factors influencing the choice of a mode are:

- Individual characteristics: A person who owns a car is more likely to travel by car (He & Thøgersen, 2017). Someone who is environmentally conscious may opt for a more sustainable mode of transport. Similarly, a student with a free public transport card is more inclined to use public transportation.

- Purpose of the trip: The reason for traveling plays a role in mode choice. For instance, someone planning to consume alcohol is unlikely to use a car. Or someone going to the shop to buy a large tv will probably not go by public transport.
- Trip characteristics: These include both quantitative factors, such as travel time and cost, and qualitative factors, such as comfort, convenience, reliability, and perceived safety and security.

In public transport research, users are often categorized into two groups: captive and non-captive (or choice) users. Captive users have no alternative transport options and are therefore reliant on public transport. Their dependence is often determined by individual characteristics as well as the purpose of the trip. Non-captive users, on the other hand, have access to alternative modes of transport, meaning their mode choice is based on a trade-off between the characteristics of the available options.

This literature review will further focus on the factors influencing public transport usage, particularly for buses. More specifically, it examines how trip characteristics affect the mode choice of non-captive users and how the adoption of articulated buses contributes to these characteristics.

3.3. Trip characteristics influencing urban bus ridership

Many research is conducted on attributes influencing the patronage of the bus. According to the literature the most convenient attributes are travel time, trip fare, reliability, frequency and comfort. More recent papers also show that environmental considerations is becoming a more siginificant attribute. Safety is another frequently cited factor; however, its significance appears to be more pronounced outside of Europe. Nevertheless, in Edinburgh, safety was identified as a significant concern, as passengers reported frequent encounters with intoxicated and disruptive individuals on buses, which negatively impacted their perceived satisfaction and overall travel experience (Stradling et al., 2007)

Table 3.1 provides an overview of the consulted literature, summarizing the significant factors influencing LoS in urban bus transport systems. It summarises the significant factors found for bus patronage in a specific area of the world.

Table 3.1: Summary of Key Factors Influencing Bus Transport Usage

Source	**Mode**	**Location**	**Significant Factors**
Cascajo and Monzon, 2014	Urban Bus	Multiple European Cities (Bremerhaven, Budapest, Madrid, Gothenburg, Rouen)	Traveltime, Frequency, Comfort, Information, Reliability, Safety, Environmental impact
Currie and Wallis, 2008	Bus	Brussels, Madrid, Bilbao, Aalborg, Turin, Skane	Frequency, Traveltime, Reliability, Comfort, Information, Trip fare
Suleiman et al., 2023	Bus	Oviedo, Spain	Comfort, Information, Frequencies, Start- and end times, Reliability, Trip fare
Tyrinopoulos and Antoniou, 2013	Not Specific	Kalamaria, Greece	Traveltime, Reliability, Connections, Crowding, Comfort, Trip fares
Beirão and Sarsfield Cabral, 2007	Not Specific	Porto, Portugal	Traveltime, Reliability, Crowding, Frequency, Information
Sterman and Schofer, 1976b	Urban Bus	São Paulo, Rio de Janeiro, Belo Horizonte, Curitiba, Fortaleza, Goiânia, Porto Alegre, Recife, Salvador (Brazil)	Reliability, Fares, Safety
Stradling et al., 2007	Urban Bus	Edinburgh, UK	Reliability, Comfort, Drivestyle, Information, Safety
Liu and Sinha, 2007	Urban Bus	York, UK	Reliability, Fares, Safety
Cheranchery et al., 2018	Urban Bus	Kolkata, India	Cleanliness, Safety, Comfort, Headway Variance
Suman et al., 2016	Bus	Delhi, India	Crowding
Agarwal and K, 2010	Urban Bus	Bhopal, India	Operational Efficiency, Fleet Size, Route Optimization, Environmental Impact
Sogbe et al., 2024	Urban Bus	Various Developing Countries	Safety, Security, Comfort, Reliability, Accessibility
Rohani et al., 2013	Bus	Singapore	Waiting Time, Travel Time, Reliability
Susilawati and Nilakusmawati, 2017	Bus	Bali, Indonesia	Safety and Comfort, Responsiveness, Capacity, Tangibility, Reliability
Deb and Ali Ahmed, 2018	Bus	Agartala, India	Safety, Comfort, Accessibility, Timely Performance
Sterman and Schofer, 1976a	Urban Public Transport	Chicago, USA	Reliability
Ma et al., 2013	Bus	Various	Reliability

3.4. Quality of Service (QoS)

Many of the previously noticed attributes are captured in an overarching concept called Quality of Service (QoS).

QoS refers to the overall effect produced by the performance of a service, which ultimately determines the degree of user satisfaction (Perez, 2017). Maintaining a high QoS is essential for transport providers, as it attracts more passengers, whereas a low QoS discourages people from using public transport (Das & Pandit, 2015).

QoS can be assessed from the passenger's perspective, encompassing both measured (objective) and perceived (subjective) performance indicators of a transit system. However, measuring QoS can be challenging, as it includes both quantitative factors (e.g., frequency, travel time, reliability) and qualitative aspects (e.g., comfort, convenience, safety) (Hensher et al., 2003). To systematically evaluate transit performance, the Transit Capacity and Quality of Service Manual (TCQSM) provides a structured framework.

One of the key methodologies in the TCQSM is the Level of Service (LoS) concept, which quantifies transit performance of fixed-route systems using a six-tier grading system. LoS assigns grades ranging from A (best performance) to F (poor performance). A higher LoS rating (e.g., A or B) signifies a well-functioning and efficient system, whereas a lower rating (e.g., E or F) represents undesirable conditions from the passenger's viewpoint (Kittelson & Associates et al., 2013).

While QoS describes the overall transit experience, LoS provides a standardized measurement framework to evaluate and compare QoS.Table 3.2 presents the fixed-route QoS framework. QoS is determined based on availability as well as comfort & convenience. Both factors have specific indicators for measuring these aspects. For availability, this study will focus specifically on frequency, as the introduction of articulated buses will lead to a reduction in headway.

Table 3.2: Indicators of the QoS (Kittelson & Associates et al., 2013)

Availability	Comfort & Convenience
Frequency	Travel Time
Service Span	Reliability
Access	Passenger Load

3.4.1. Availability

Availability is a fundamental determinant of transit service quality, as it dictates whether public transportation is a viable option for potential users. The TCQSM identifies three key factors that influence availability: frequency, service span, and access (see Table 3.2). These elements define whether transit is accessible in both spatial and temporal terms.

Frequency (or headway) refers to how often vehicles arrive at a given stop within a certain timeframe. It is typically measured in headways, which represent the time interval between consecutive vehicles on a given route. Service Span defines the operational hours of transit services, indicating how early and how late a service runs during a given day. A longer service span ensures that passengers can rely on public transport for both outbound and return trips, accommodating a wider range of travel needs. Access refers to the physical proximity of transit stops to users' origins and destinations. It also encompasses supporting infrastructure for first- and last-mile connectivity, such as pedestrian walkways, bicycle facilities, and park-and-ride options.

Together, these factors determine whether transit is a practical choice for users. When availability is constrained—whether due to low service frequency, limited operating hours, or inadequate access—potential passengers may opt for alternative transportation modes or forgo travel altogether. Ensuring sufficient availability is thus critical to maintaining ridership levels and enhancing perceived QoS.

For this literature study the focus on availability will be limited to frequency, as the introduction of articulated buses is expected to result in a decrease in headway. The service span is assumed to remain unchanged, as the implementation of articulated buses does not affect the operational hours of transit services. While the introduction of articulated buses may influence access, particularly if bus stops are relocated or modified, this effect falls outside the scope of this project.

3.4.2. Comfort & Convenience

Beyond availability, comfort and convenience are essential dimensions of transit service quality that influence passengers' decisions to use public transportation. The TCQSM defines three key factors affecting comfort and convenience: passenger load, reliability, and travel time (Table 3.2).

Passenger load refers to the number of passengers on board relative to vehicle capacity. It indicates the level of space available for each passenger and is commonly used to assess occupancy conditions in public transport vehicles. Reliability represents the consistency of transit service in terms of schedule adherence and punctuality. It is measured by deviations from scheduled arrival and departure times and reflects the predictability of service. Travel time encompasses the total duration of a transit trip, including waiting, in-vehicle, and transfer times. It is a key factor in assessing the efficiency of a transit service and is often used to compare different transport modes. Travel time of public transit modes tends to be split into waiting time, in-vehicle time, transfer time, and others (Carrion & Levinson, 2012). The quality of service measure is the transit-auto travel time ratio, the in-vehicle transit travel time divided by the in-vehicle single-occupant auto travel time for a given trip (Kittelson & Associates et al., 2013).

As it is expected that the introduction of articulated buses will effect the reliability and passenger loading significantly these indicators related to comfort and convenience will be reviewed in the literature to establish a comprehensive understanding. The LoS scores for these attributes are presented in Tables **??** to 3.4.

3.5. Service Frequency

Service frequency, often defined by headway, is a key factor influencing mode choice, as research indicates that higher bus frequencies lead to increased ridership (Berrebi et al., 2021; Kashfi et al., 2015; Santos et al., 2013). A primary reason for this effect is that shorter headways reduce waiting and transfer times, enhancing multimodal connectivity and making public transport a more attractive option (Kashfi et al., 2015). Additionally, lower headways improve network resilience, as service disruptions have a less severe impact when buses arrive more frequently. Conversely, longer headways significantly increase passenger waiting times at disturbances, which is considered highly undesirable.

While increasing service frequency offers clear benefits, it also entails substantial investment costs, as additional vehicles and drivers are required to sustain the higher capacity. Moreover, excessively high frequencies may reduce operational efficiency and profitability, as the cost of additional services does not always correspond to a proportional increase in ridership (Yu et al., 2017). Furthermore, higher frequencies increase the likelihood of bus bunching, a phenomenon where vehicles become unevenly spaced due to factors such as traffic congestion, stochastic passenger demand, and variations in operating conditions (Chen et al., 2022; Iliopoulou et al., 2018; Soza-Parra et al., 2019). Bus bunching can cause a cycle which exacerbates service irregularity, causing more passengers to experience a lower QoS due to uneven vehicle loads which due to the fact that delayed buses pick up not only their scheduled passengers but also those who would have boarded the following bus. As a result, the delayed vehicle becomes increasingly overcrowded and falls further behind schedule, while the next bus encounters fewer passengers and moves ahead more quickly (Kittelson & Associates et al., 2013).

The TCQSM manual establishes a link between headway duration and Level of Service (LoS), as shown in Table 3.3.

Table 3.3: Headway Levels of Service (LoS) (Kittelson & Associates et al., 2013)

LoS	Average headway (min)	Vehicles per hour	Comments
A	$<$10	$>$6	Passengers do not need schedules
B	10-14	5-6	Frequent service, passengers consult schedules
C	15-20	3-4	Maximum desirable wait time if a bus is missed
D	21-30	2	Service unattractive to choice riders
E	31-60	1	Service available only once per hour
F	$>$60	$<$1	Service unattractive to all riders

3.6. Reliability

Travel Time Reliability (TTR) plays a crucial role in travel behavior, as variability in travel time increases the risk of passengers missing connections or arriving late, leading to additional costs and reduced utility (Chakrabarti & Giuliano, 2015). The main sources of unreliability include headway variance (bus bunching) and unexpected waiting times (Soza-Parra et al., 2019). Additional factors affecting reliability are traffic conditions, vehicle quality, driving skills, environmental conditions, and vehicle/staff availability (Kittelson & Associates et al., 2013). Passenger load also plays a significant role, which will be discussed in a later section.

Research shows that TTR can be equally or even more important than actual travel time (Zang et al., 2022). A poorly performing public transport system with low punctuality and irregular scheduling often leads to decreased usage and a shift to alternative transport modes. This effect is not only observed in public transport but also among car users: when they experience unreliable travel times due to traffic congestion, a modal shift towards public transport can occur (Sweet & Chen, 2011).

3.7. Passenger Load

Passenger load, or in-vehicle crowding, is a critical factor influencing travel choice behavior and is considered one of the most important determinants of mode choice, alongside travel time and cost (Shao et al., 2022). While a high occupancy rate may indicate strong demand for transit services, excessive crowding often makes public transport less attractive to passengers (Perk et al., 2001). The study of Soza-Parra et al. (2019) even highlighted that crowding has a negative non-lineair effect on the satisfaction, implying that the more crowded it becomes, the more the negative perception. This is because crowding plays a central role in transit QoS. Crowding directly impacts comfort and convenience, as high occupancy levels can affect multiple aspects of public transport operations, including operating speed, waiting time, and travel time reliability. Additionally, passenger load influences well-being, comfort, and perceived time savings (Tirachini et al., 2013). The TCQSM manual specifies the LoS associated with crowding, as shown in Table 3.4.

Table 3.4: Passenger Load Levels of Service (LoS) (Kittelson & Associates et al., 2013)

LoS	Load Factor	Standing Passenger Area (m^2/p)	Comments
A	0.00-0.50	>1.00*	No passenger needs to sit next to another
B	0.51-0.75	0.76-1.00*	Passengers can choose where to sit
C	0.76-1.00	0.51-0.75*	All passengers can sit
D	1.01-1.25**	0.36-0.50	Comfortable standee load for design
E	1.26-1.50**	0.20-0.35	Maximum schedule load
F	>1.50**	<0.20	Crush load

* Used for vehicles designed to have most passengers standing.
** Approximate value for comparison, for vehicles designed to have most passengers seated. LoS is based on area.

3.7.1. Effect Crowding on Reliability

As earlier mentioned, the main source of unreliability is found in headway variance (bus bunching) and unexpected waiting times. A substantial body of research has examined the effects of crowding on transit operations, particularly its impact on dwell time. Studies indicate that dwell time increases with the square of the number of standees inside a bus, multiplied by the total number of passengers boarding and alighting at a stop (Tirachini et al., 2013). This implies that crowding has a significant effect on operations and could force headway variations, causing unreliability.

The study by Fletcher and El-Geneidy (2013) examined the effects of crowding in more detail and found that when 60% of a bus's capacity is filled, the effects of crowding on dwell time become more pronounced. This finding is also somewhat implied in the study by Katz and Garrow (2012), where it is argued that crowding itself does not necessarily lead to higher dwell times, but that door crowding is the primary cause. Their study also highlighted the importance of bus design, noting that factors such as aisle width, door placement, and overall vehicle layout significantly influence boarding efficiency and passenger flow.

In the event of severe overcrowding, this may also lead to denied boardings, where passengers are unable to board the first arriving vehicle due to capacity constraints (Tirachini et al., 2013; Yap & Cats, 2021). Although the TCQSM manual does not explicitly include denied boardings in its definition of service reliability, studies suggest that passengers who experience boarding difficulties due to overcrowding perceive a significant decline in service quality (Katz & Garrow, 2012).

3.7.2. Comfort

Comfort is widely recognized as a crucial determinant of transit service quality, and improving comfort has been identified as an effective strategy for attracting more passengers (Barabino, Eboli, et al., 2019; Eboli et al., 2016). While comfort is often considered a qualitative attribute, research suggests it can be quantitatively assessed based on various factors, with crowding levels being the most significant. High in-vehicle density negatively affects passenger satisfaction, as it increases the likelihood of standing and reduces personal space. Passengers experience discomfort due to over-closeness, which can induce stress and a perceived loss of control. Additionally, studies suggest that crowded conditions limit passengers' ability to engage in productive or relaxing activities, further reducing overall satisfaction (Haywood et al., 2017).

Beyond passenger load, several external factors influence comfort, including vibrations, noise, temperature, and driver behavior (Barabino, Coni, et al., 2019). Shen et al. (2016) found that trip duration also plays a key role in perceived comfort, particularly for standing passengers. Their study revealed that as travel time increases, perceived comfort declines, with prolonged trips exacerbating the discomfort caused by crowding. Drabicki et al. (2023) further found that 50–70% of passengers may choose to skip an overcrowded bus or tram and wait for a less crowded one, further illustrating the impact of passenger load on travel behavior.

3.7.3. Perceived Travel Time

Many studies indicate that travel time is a key determinant of mode choice. However, another important aspect of travel time is the perceived travel time (PTT). PTT refers to the duration that the passenger felt that he/she was spending between the departure and arrival. This is an important factor because passengers make decisions based on their perceived rather than actual travel time (González et al., 2015). Studies highlighted that in urban public transport passengers often over-perceive the true travel time (Brands et al., 2022; Meng et al., 2018). This overestimation could be explained by one of the classical findings of Vierordt (1868) which showed that short activities were usually overestimated while long activities were usually underestimated. This is also shown in the study of Mishalani et al. (2006) where it was shown that passengers perceive waiting time to be greater than the actual amount of time waited.

In addition to increasing actual travel time, crowding has been shown to increase PTT, making journeys feel longer than they are (Sadeghi et al., 2023; Shafaati & Saffarzadeh, 2024). Yap et al. (2025) found that passengers' evaluation of crowding became more negative after the COVID-19 pandemic, suggesting that perceived travel time is now even more adversely affected by high passenger loads. Furthermore, research indicates that travelers experiencing severe crowding are often willing to pay extra to reduce their travel time, highlighting that crowding levels directly impact the Value of Time (VoT) (Li & Hensher, 2011; Shao et al., 2022).

3.7.4. Safety

High crowding levels can negatively impact both perceived and actual passenger safety. Studies indicate that overcrowded buses increase the risk of unsafe boarding and alighting, as passengers may struggle to enter and exit vehicles efficiently. Additionally, a high passenger load increases the risk of driver distraction, reducing their ability to focus on the road and increasing the likelihood of accidents (Firm, 2025). Moreover, high passenger density raises the likelihood of falls, collisions, and conflicts, particularly in situations involving sudden braking or emergency evacuations.

Beyond physical safety, health risks have become more prominent, especially following the COVID-19 pandemic. Travelers are now more aware of virus transmission in enclosed, crowded spaces. A high passenger index increases the risk of infection spread, making overcrowded public transport an ongoing concern for many users (Tirachini & Cats, 2020).

Furthermore, overcrowding heightens perceived insecurity, particularly during off-peak hours or in poorly lit areas, where passengers may feel vulnerable to pickpocketing or sexual harassment. These crimes are more prevalent in overcrowded public transport, as the lack of personal space makes it easier for thieves to operate unnoticed. Additionally, passengers in tight, confined spaces tend to be less aware of their belongings, further increasing the risk of theft and personal security concerns (Ceccato et al., 2022).

4 Impacts of Crowding

This chapter focusses on providing a clearer definition of the effects of crowding in a bus network and how this impacts the passenger and operator. In order to find this holistic view, findings from the literature review will be used and additionaly interviews with key stakeholders involved with the bus exploitation in the RET will be executed.

Eventually all the findings will be sumarised in a causal loop diagram (CLD) which illustrates all the relations between the factors and subsequently the diagram will offer insights into the expected impacts of implementing the articulated bus solution. Moreover in this chapter the following subquestion is answered.

- *How does crowding affect operations from both a passenger and operator perspective?*

4.1. Interviews with key stakeholders

Within the RET there are several important departments which all have their view on the current situation. These departments are Strategic & Development, Asset Management, Maintenance management and the bus operators. The following questions has been proposed to them:

4.1.1. Bus operators

The first interview was conducted with the coordinator responsible for addressing operational concerns raised by bus drivers. In this role, the interviewee collects and communicates complaints from drivers to the public transport operator's central office. As the coordinator is also an active bus driver, he possesses firsthand insight into the challenges experienced on the road.

According to the respondent, several service lines currently experience passenger demand that exceeds the capacity of conventional 12-meter buses. This mismatch leads to multiple operational and service-related challenges. Passengers face reduced service quality due to overcrowding, which may prompt them to shift to alternative modes of transport, resulting in revenue loss for the operator. Moreover, the increased density on board contributes to elevated stress levels and, in some cases, aggressive behaviour towards drivers.

The issue is particularly pronounced on lines with high concentrations of school-aged passengers, where peak demand is both intense and temporally concentrated.

To mitigate these problems, the interviewee suggested the deployment of 18-meter articulated buses. This approach would allow the operator to accommodate higher passenger volumes without increasing the number of drivers required, thereby easing pressure on the system and improving conditions for all stakeholders involved.

4.1.2. Strategic and Development department

The Strategic and Development (S&D) department of RET has highlighted that the current bus network is experiencing capacity challenges due to a shortage of bus drivers. However, the S&D department holds a different perspective, arguing that these capacity issues are concentrated on only a few specific routes and occur primarily at certain times, often in a single direction.

S&D suggests that reducing service frequency during morning peak hours while deploying articulated buses could help manage capacity constraints. While this approach may lead to a reduction in non-captive passengers during peak hours, it is expected to attract more passengers during non-peak periods due to an overall improvement in service quality.

Although S&D acknowledges that articulated buses could address the current capacity issues, they remain cautious about potential drawbacks. A key concern is the impact on network efficiency, as articulated buses would be limited to specific high-demand corridors. This restriction could reduce operational flexibility in deploying buses across the network, potentially lowering overall efficiency. As a result, S&D believes that this solution would be more suitable for a network exclusively serving high-demand corridors.

4.1.3. Maintenance manager

The asset manager acknowledged that the bus network is experiencing capacity constraints, largely due to a shortage of drivers. Overcrowded buses are contributing to a decline in perceived service quality, prompting non-captive travellers to seek alternative modes of transport. Key factors undermining service quality include low levels of comfort and poor reliability, such as denied boarding and inconsistent on-time performance.

Articulated buses are regarded as a viable solution for addressing these challenges in both the short and long term. However, concerns were raised regarding the robustness of this approach. Operating 12-meter buses at higher frequencies offers greater system resilience, as service disruptions are more easily absorbed. When a trip is cancelled, the waiting time for the next vehicle remains relatively short. In contrast, while articulated buses provide increased capacity, the cancellation of a single trip may result in significant overcrowding and operational difficulties, making disruptions more challenging to manage.

4.1.4. Asset Manager

The asset manager, in agreement with the other stakeholders, acknowledged that certain bus lines are experiencing capacity issues. Furthermore, he noted that overcrowding also contributes to fare evasion as effective surveillance becomes challenging under such conditions. The prevalence of successful fare dodging can then encourage others to evade fares as well, resulting in a contagious phenomenon. This behaviour is also described by Haghani and Nassir (2025), who emphasise that fare evasion is not solely a financial issue; social and psychological factors also play a significant role. When passengers perceive the public transport system as unfair—due to unreliable services, high fares, or insufficient investment—the tendency to evade fares increases. This observation suggests that, while price sensitivity influences fare evasion, perceptions of fairness and service quality are equally critical factors.

4.2. Causal Loop Diagram

Building upon the findings from the literature review and the interviews conducted at RET, the next step involves visualising the causal relationships between the identified factors using a CLD.

A CLD is a qualitative tool from systems thinking that helps to map the dynamic interdependencies within a system. By identifying feedback loops, which can be either balancing or reinforcing, it becomes possible to uncover how the system behaves over time. A balancing loop, also called a negative feedback loop, tends to stabilise the system. It counteracts changes and guides the system towards a state of equilibrium. In contrast, a reinforcing loop, also referred to as a positive feedback loop, amplifies change and can lead to continuous growth or decline.

If a found loop is Balancing this will be indicated by a **B**, a reinforcing loop is indicated by a **R**.

4.3. The Effects of Crowding

As this diagram wil expand fast we will start small by saying that services with a high QoS are likely to attract more passengers and therefore increase bus ridership and costumor satisfaction.

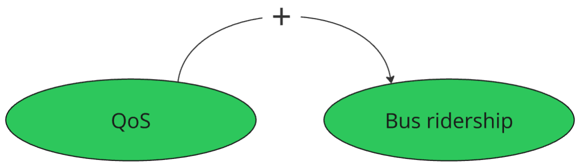


Figure 4.1: Effect Quality on Ridership

If we then expand first we will include factors which increase the QoS. Findings from the literature review on infleuncing factors yield that Traveltime, Service Delivery, Security and Safety and Availablity are factors in fluencing the quality of service. Figure 4.2 then forms the basis for our CLD. Now lets incooperate what happens when crowding in vehicles occurs. First focussed on the factors Service Delivery and Traveltime.

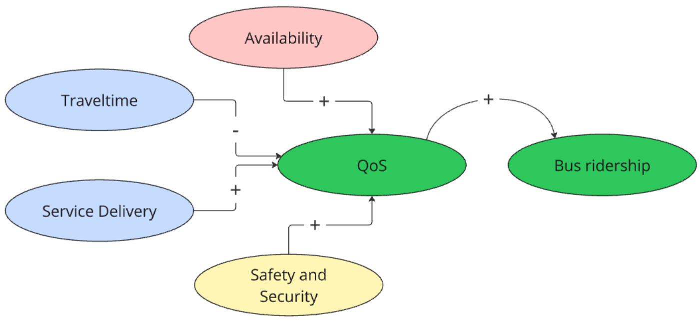


Figure 4.2: Factors influencing the QoS

4.3.1. Traveltime and Service Delivery

Figure 4.3 shows the effects of busy buses. If this partial CLD is analyzed, it can already be observed that crowding can have a significant impact on Quality of Service (QoS) as well as the efficiency of operations. The analysis starts by examining the reinforcing and balancing loops.

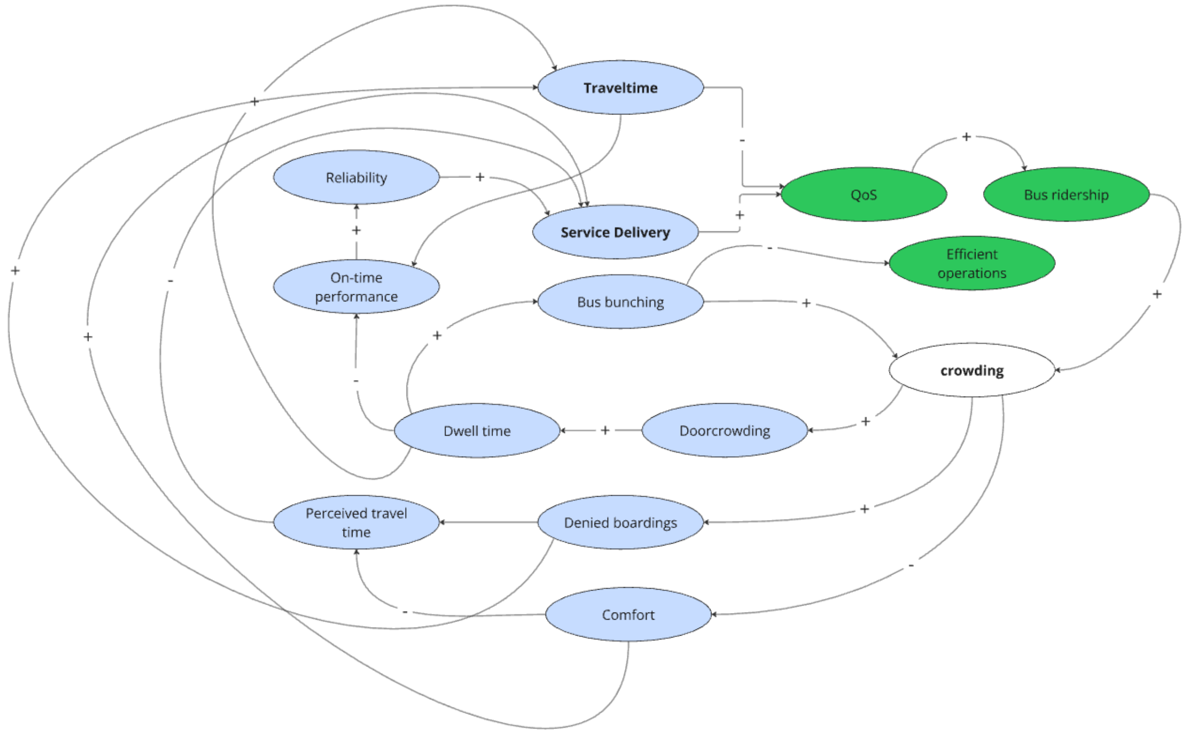


Figure 4.3: Effects of Crowding on Service Delivery and Traveltime

R1: Crowding - Doorcrowding - Dwell Time - On-time Performance - Bus Bunching

This reinforcing loop illustrates how elevated levels of crowding initiate a cascade of effects that ultimately exacerbate crowding itself. High levels of crowding encourage passengers to concentrate near the doors, resulting in increased doorcrowding. This situation prolongs dwell time as passengers experience delays during boarding and alighting. The extended dwell time negatively impacts the bus's adherence to schedule, leading to the phenomenon of bus bunching, where multiple buses arrive at stops in quick succession rather than being evenly spaced. Bus bunching leads to uneven passenger distribution across vehicles, thereby intensifying crowding conditions and contributing to operational inefficiencies.

B1: QoS - Bus Ridership - Crowding - Door Crowding - Dwell Time - On-time Performance - Reliability - Service Delivery

This balancing loop demonstrates how an increase in Quality of Service (QoS) encourages higher bus ridership, as improved service attracts more passengers. However, the resulting rise in ridership contributes to increased crowding, leading to heightened doorcrowding and extended dwell times due to delays during boarding and alighting processes. The prolonged dwell time negatively impacts the on-time performance of buses, diminishing their reliability. Reduced reliability undermines overall service delivery, consequently lowering the perceived QoS. This feedback mechanism highlights how excessive bus ridership, driven by improved QoS, can eventually lead to overcrowding, deterioration of service quality, and ultimately a reduction in ridership.

B2a, B2b, and B2c: Quality of Service - Bus Ridership - Crowding - Denied Boardings

These balancing loops illustrate how improvements in Quality of Service (QoS) can unintentionally initiate a sequence of negative impacts through the phenomenon of crowding. Enhanced QoS attracts more passengers, resulting in an increase in bus ridership. However, as ridership grows, crowding begins to escalate, eventually resulting in denied boardings when buses reach their maximum capacity.

The effects of denied boardings diverge into three separate but interconnected pathways:

B2a: Reliability Pathway. Denied boardings undermine the system's reliability by disrupting expected service delivery patterns, thereby reducing overall service delivery. A decline in service delivery negatively impacts QoS, thereby discouraging ridership and attempting to restore equilibrium.

B2b: Perceived Travel Time Pathway. Denied boardings lead to heightened perceived travel time, as passengers experience delays and increased waiting times. Longer perceived travel time diminishes overall service satisfaction and undermines QoS, which in turn reduces ridership and counteracts the initial improvement in QoS.

B2c: Travel Time Pathway. Increased denied boardings contribute directly to longer travel times for passengers who are unable to board the bus promptly. This increase in travel time further detracts from the perceived quality of service, contributing to a gradual reduction in ridership.

B3: Quality of Service - Bus Ridership - Crowding - Comfort - Perceived Travel Time - Service Delivery

This balancing loop demonstrates how improvements in Quality of Service (QoS) can lead to unintended negative consequences when the system's capacity is exceeded. Enhanced QoS encourages increased bus ridership, as passengers are attracted by better service. However, as ridership grows, crowding begins to intensify within the buses.

The rise in crowding directly affects passenger comfort, as overcrowded conditions reduce the overall satisfaction and experience of passengers. Reduced comfort subsequently increases perceived travel time, as passengers feel the journey to be longer and more unpleasant due to overcrowded conditions. As perceived travel time increases, the overall service delivery is negatively affected, leading to a reduction in QoS. This feedback mechanism serves as a balancing loop, where an initially improved QoS, when overwhelmed by demand, ultimately deteriorates due to reduced comfort and heightened perceived travel time.

4.3.2. Safety and Security

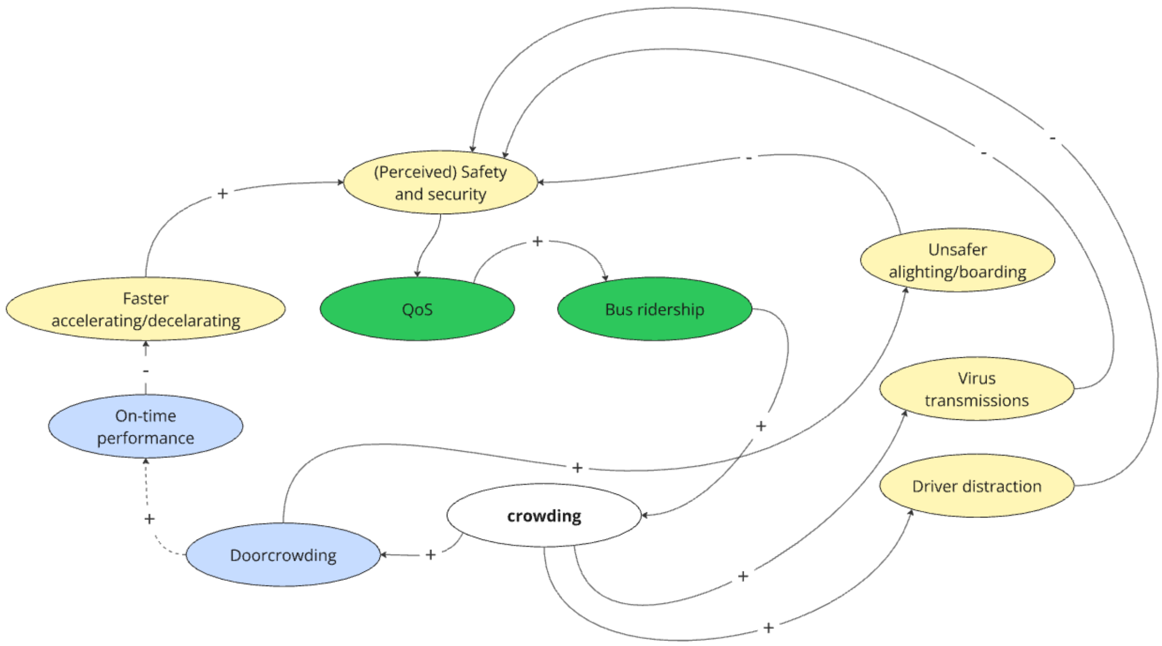


Figure 4.4: Effects of Crowding on Safety and Security

B4: Bus Ridership - Crowding - (Perceived) Safety and Security

Passenger perceptions of safety and security on buses can be negatively affected by factors such as overcrowding, reduced personal space, and the potential for unsafe interactions among passengers. These factors may reduce the overall comfort and security of the journey, subsequently diminishing the perceived quality of service (QoS). As the perceived safety and security decrease, bus ridership is likely to be adversely affected.

B5: Bus Ridership - Crowding - Driver Distraction / Virus Transmission - Safety and Security - QoS

This balancing loop illustrates the complex relationship between increasing bus ridership and its impact on crowding. As ridership increases, crowding within buses becomes more pronounced, which in turn negatively impacts the perceived safety and security of passengers. This heightened crowding may also contribute to greater distraction among bus drivers, leading to potentially hazardous driving conditions. Moreover, in the context of the COVID-19 pandemic, passengers are more acutely aware of the risks associated with virus transmission in crowded environments. This awareness further diminishes the perceived safety and security, thereby reducing the overall QoS. Consequently, the lowered QoS negatively influences bus ridership, creating a feedback loop.

B6: Bus Ridership - Crowding - Door Crowding - Unsafe Boarding/Alighting - (Perceived) Safety and Security - QoS

In this loop, increasing levels of crowding lead to congestion at bus doors, which complicates the boarding and alighting processes. This congestion increases the likelihood of unsafe interactions or accidents, such as passengers jostling or struggling to board or alight in a timely and safe manner. These safety concerns erode the perceived safety and security of the bus journey, ultimately resulting in a diminished QoS. As a consequence, bus ridership may decline.

B7: Bus Ridership - Crowding - Door Crowding - On-time Performance - Faster Acceleration/Deceleration - (Perceived) Safety and Security - QoS

This loop illustrates how crowding and door congestion can negatively impact a bus's on-time performance. The need to compensate for delays due to overcrowding may compel bus drivers to accelerate or decelerate more rapidly. Such driving behaviours, in turn, increase the perceived risk associated with the journey, diminishing the sense of safety among passengers. As passengers' perceptions of safety decline, so too does the QoS, leading to a reduction in ridership. This creates a reinforcing cycle of diminished service quality.

4.3.3. Availability

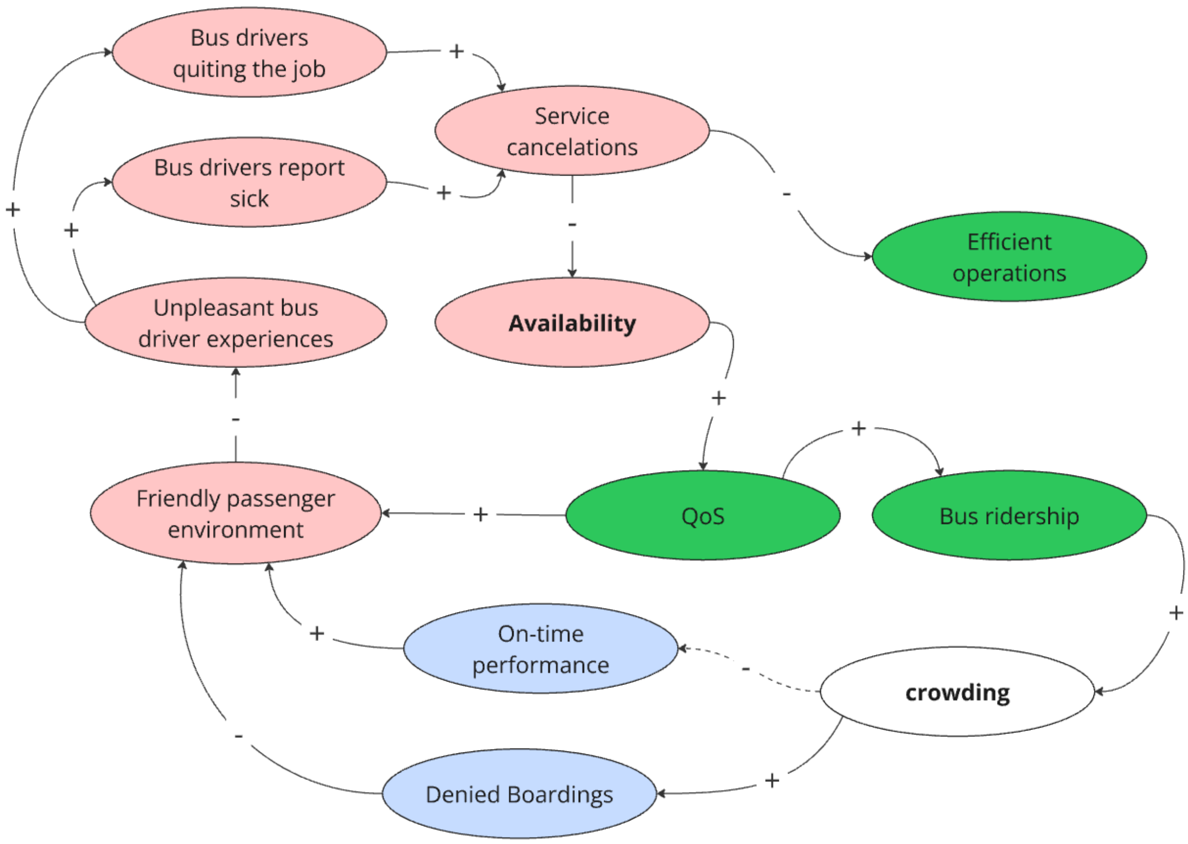


Figure 4.5: Effects of Crowding on Availability

R2: QoS - Friendly Passenger Environment - Unpleasant Bus Driver Experiences - Bus Drivers Reporting Sick/Bus Drivers Quitting the Job - Service Cancellations - Availability

This reinforcing loop demonstrates how a decline in Quality of Service (QoS) can negatively impact the work environment for bus drivers, resulting in a series of adverse effects. Reduced QoS lowers the overall friendliness of the passenger environment, which can increase the frequency of unpleasant interactions for bus drivers. Negative experiences among drivers contribute to higher rates of drivers reporting sick or quitting their jobs entirely. As more drivers are unavailable, service cancellations increase, which diminishes overall availability. Reduced availability further undermines QoS, creating a self-reinforcing cycle of deteriorating service quality and declining workforce stability.

B: QoS - Bus Ridership - Crowding - On-time Performance/Denied Boardings - Friendly Passenger Environment - Unpleasant Bus Driver Experiences - Bus Drivers Reporting Sick/Bus Drivers Quitting the Job - Service Cancellations - Availability

This balancing loop illustrates how increases in Quality of Service (QoS) attract more passengers, thereby increasing bus ridership. However, higher ridership levels contribute to crowding, which negatively affects on-time performance and increases the likelihood of denied boardings. As passengers face difficulties boarding buses or experience delays, the friendliness of the passenger environment decreases, leading to a rise in unpleasant interactions between passengers and bus drivers. Negative experiences among drivers contribute to higher rates of drivers reporting sick or quitting their jobs, ultimately resulting in more service cancellations and decreased availability. Reduced availability lowers QoS, thereby discouraging ridership and restoring balance within the system.

4.3.4. Operator related effects

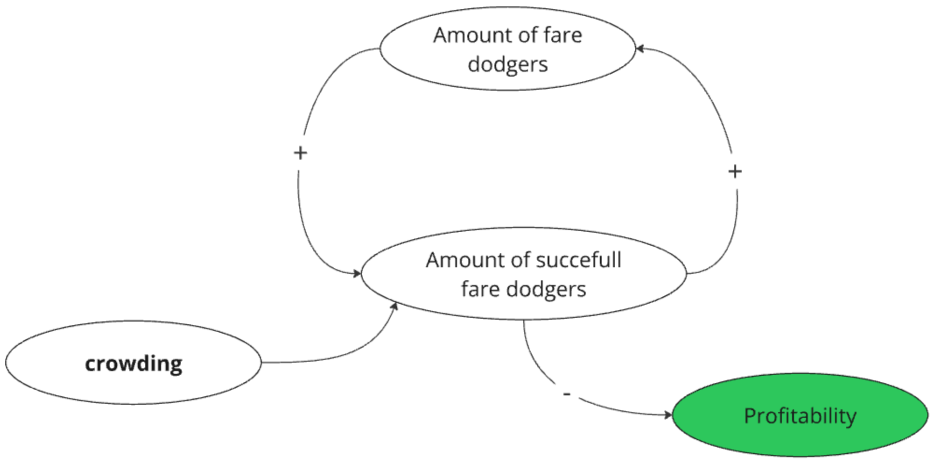


Figure 4.6: Relation of Crowding and Fare Dodgers

R3: Crowding - Amount of Fare Dodgers - Amount of Successful Fare Dodgers - Profitability

This reinforcing loop illustrates how crowding negatively influences the profitability of public transportation systems by enabling fare evasion. As crowding increases, the ability to monitor and enforce fare payments diminishes, resulting in a rise in the amount of fare dodgers attempting to evade payment.

The increase in fare dodgers leads to a higher amount of successful fare dodgers—those who successfully avoid paying the fare without being detected. As the number of successful fare dodgers grows, profitability declines due to revenue losses from unpaid fares. The reduced profitability further limits the financial capacity to invest in monitoring systems or to implement measures that could alleviate crowding, thereby perpetuating the cycle of fare evasion and profitability decline.

4.4. Merging the proposed solution

If the proposed solution, involving the introduction of articulated buses and the reduction of service frequency, is implemented, several expected outcomes can be anticipated. The increased vehicle capacity offered by articulated buses would help to alleviate crowding levels. With reduced crowding, passengers would experience greater comfort during their journey, while the reliability of the service would improve due to enhanced on-time performance and a reduction in denied boardings. Additionally, the decrease in denied boardings would lead to shorter travel times, thereby increasing the overall QoS. This improved reliability would further contribute to a higher level of service delivery, which, in turn, would enhance the QoS.

Beyond improvements in service delivery, the higher reliability would foster a more conducive passenger environment, characterised by a reduction in unpleasant experiences with bus drivers. This improvement in the working conditions for drivers would likely reduce turnover rates and absenteeism due to illness, ultimately improving driver availability. Consequently, this would further elevate the QoS.

However, it must be noted that the reduction in service frequency, when compared to the use of articulated buses alone, may have an adverse effect on availability. A lower service frequency would result in longer waiting times for passengers, which could negatively affect the QoS and lead to a shift towards alternative modes of transport. On the positive side, a decrease in service frequency would reduce the likelihood of bus bunching, as there would be more space between vehicles, potentially improving the overall flow of the network.

Moreover, the deployment of articulated buses on specific routes, rather than across the entire network, may result in a reduction in network efficiency. This is because these buses are restricted to operating on designated routes, limiting their flexibility. Consequently, they cannot be reassigned to other routes where additional capacity is needed, such as in cases where a bus breaks down or becomes unavailable. This limitation reduces the network's adaptability, as articulated buses cannot serve as substitute vehicles during periods of high demand or operational disruptions. As a result, the system's overall responsiveness to shifting passenger demands across the network is diminished.

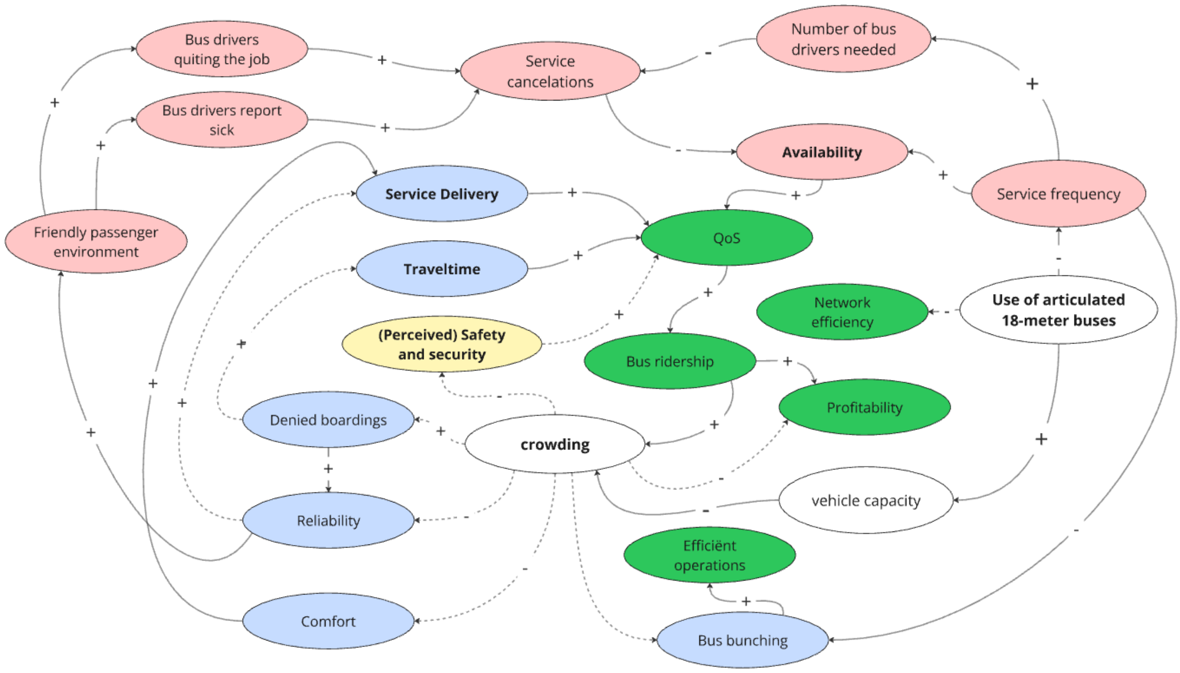


Figure 4.7: Effects of Articulated Buses

4.5. Complete CLD

On the following page, an overview of the complete CLD is presented. All the partial CLDs have been integrated into a single conceptual model, which illustrates the interrelationships between the factors influencing the QoS and the challenges currently faced by RET. Furthermore, the proposed solution is linked to these challenges within the model.

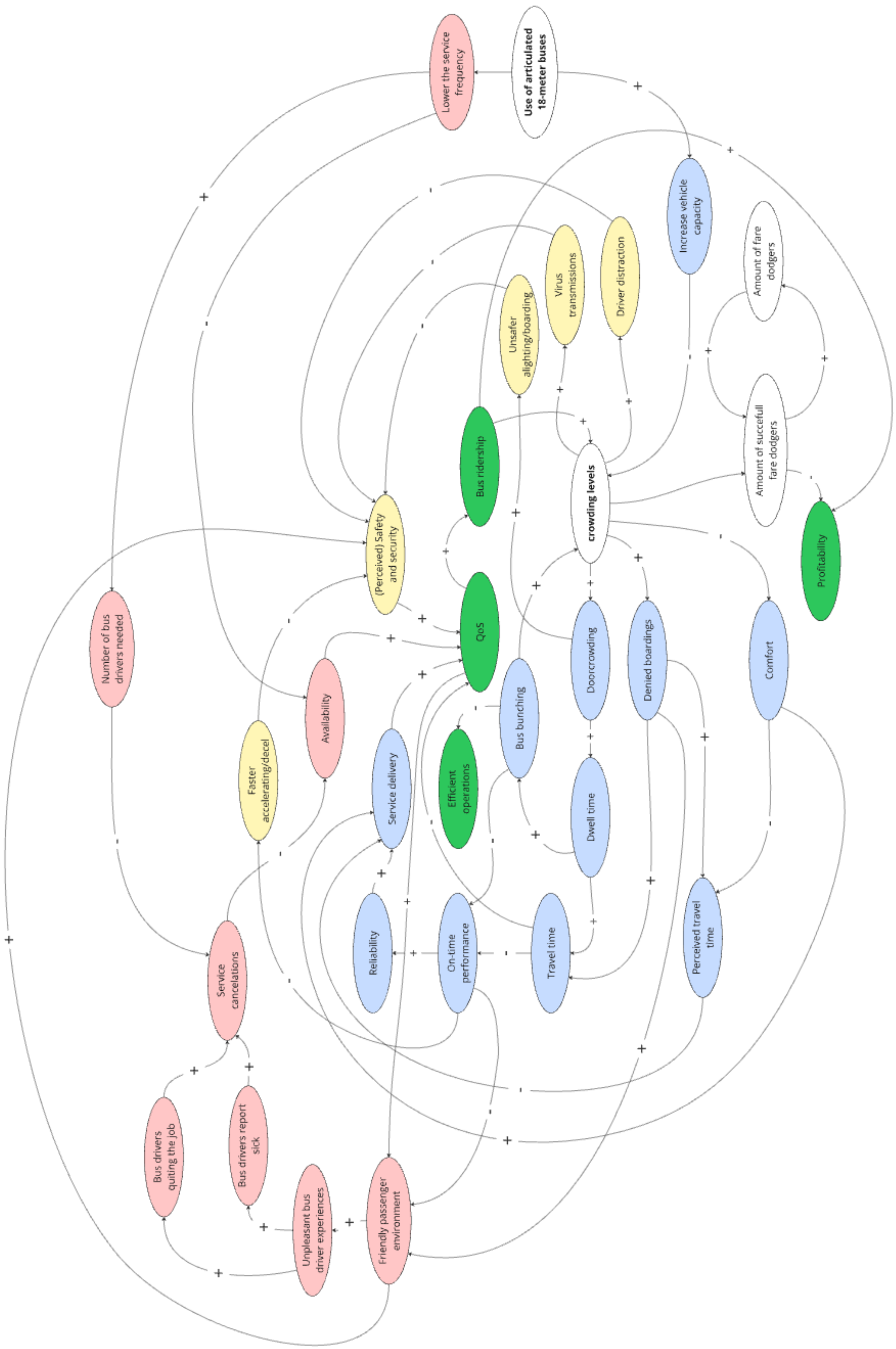


Figure 4.8: Complete CLD illustrating the relationships between factors influencing the QoS and the challenges faced by RET, along with the proposed solution.

4.6. Conclusion on the Impacts of Crowding

Through an analysis of the literature and insights gathered from interviews, a CLD was constructed, illustrating the relationships between the factors that influence the QoS of a bus network. From this, it can be concluded that crowding has significant negative impacts on both passengers and operators. Specifically, crowding leads to unreliable services due to poor on-time performance, which is primarily caused by increased dwell times, as well as denied boardings when buses are full. This, in turn, results in longer travel times, further diminishing the QoS. Furthermore, crowding reduces comfort, heightening the perceived travel time and thereby lowering service delivery, which contributes to a decrease in QoS.

Crowding also negatively affects operational efficiency, as the likelihood of bus bunching increases due to extended dwell times. As demonstrated in Figure **??**, this phenomenon forms a reinforcing feedback loop, where bus bunching exacerbates crowding in certain vehicles, while others remain under-utilised, further diminishing operational efficiency.

Regarding vehicle availability, the issues of denied boardings and unreliable services contribute to a more hostile passenger environment. This environment results in higher rates of bus driver absenteeism or resignation. The ensuing driver shortages lead to the cancellation of more services, thereby reducing vehicle availability and ultimately lowering QoS. This process is amplified within a reinforcement loop for captive passengers (those with no alternative transport options) where increasing driver unavailability further reduces service quality. Non-captive passengers, conversely, are likely to switch to alternative modes of transport, thereby decreasing overall bus ridership.

In terms of safety and security, crowding creates conditions that may increase the likelihood of unsafe situations. Factors such as faster acceleration and deceleration, heightened awareness of virus transmission risks, and driver distractions contribute to these risks. While these issues may not significantly affect the general passenger population, they could influence more vulnerable groups, such as the elderly, who may opt against using the bus due to perceived safety concerns.

Finally, the introduction of articulated buses and the reduction of service frequency are expected to mitigate the issues of crowding by increasing vehicle capacity. This is anticipated to improve passenger comfort and reliability, leading to a reduction in denied boardings, shorter travel times, and a more positive passenger environment. These improvements would also reduce driver turnover and absenteeism. However, reducing service frequency may negatively affect vehicle availability, resulting in potentially prompting passengers to seek alternative transport options. Additionally, restricting articulated buses to specific routes could limit network flexibility, as these buses cannot be redeployed to meet changes in demand or operational disruptions across the network.

5 Considerations Framework

This chapter addresses the subquestion: *What could be consideration framework for the deployment of articulated buses?* This section synthesises the findings from the HTM and GVB interviews into an consideration framework for the deployment of articulated buses. The framework is structured around key operational, infrastructural, and organisational themes identified during the interviews. These themes represent the main dimensions public transport operators should consider when evaluating the suitability and implementation of articulated vehicles.

The full interviews with GVB and HTM in order to create this framework can be found in Appendix B.

5.1. Trade-offs and decision making

To gain insight into the consideration framework, interviews were conducted with two Dutch public transport operators: HTM (The Hague) and GVB (Amsterdam). GVB has already been operating articulated buses for several years, whereas HTM is currently in a transition phase, introducing articulated buses on four lines.

The first operator consulted was HTM, which operates in The Hague. At the time of the interview, the introduction of articulated buses was still in a testing phase, meaning the full network effects were not yet visible. Nevertheless, the considerations and motivations behind HTM's decision provided useful insights for evaluating the suitability of articulated buses in other contexts.

Unlike RET, HTM does not operate a metro system; the tram is the backbone of the network. However, on certain buses are the main transport mode. These routes often experience overcrowding during peak hours. HTM's main challenge is not a shortage of drivers, but insufficient vehicle capacity. Increasing service frequency was deemed unsuitable, as it would likely worsen bus bunching. Therefore, deploying articulated buses was considered necessary, especially given anticipated passenger growth due to urban expansion.

Similar to RET's proposed approach, the introduction of articulated buses by HTM is accompanied by a reduction in service frequency. While this may lead to a potential loss of passengers during peak hours due to lower service availability, HTM anticipates that the overall service quality will improve, especially during off-peak hours, potentially attracting additional passengers during these periods.

GVB, like RET, does operate a metro system. However, unlike in Rotterdam, the metro in Amsterdam is not the backbone of the public transport network. It forms a ring around the city, with only the North–South line partially entering the city centre. As a result, many areas depend heavily on buses (or trams) to reach the city centre and therefore these service lines can be very crowded. This structural difference is a key reason for GVB's use of articulated buses. The combination of high bus demand and limited metro coverage makes high-capacity buses a practical solution. Standard buses would require even higher frequencies, which is operationally inefficient due to the risk of bus bunching and driver shortages. Articulated buses help mitigate these issues.

Figure 5.1: Articulated bus operated by HTM

Figure 5.2: Articulated bus operated by GVB

Together, HTM's transition phase and GVB's established experience offer complementary perspectives that are valuable for the development of the consideration framework.

5.1.1. Capacity

An important findings which answers why the interviewed operator have chosen in their time to deploy articulated buses in their public transport network was mainly driven by purposes.

First of all, the main point that was told is that to many passengers wanted to use the bus, in other words: there was too much passenger demand to fullfill with the current capacity. Then for operators the question they should ask theirself is how are we going to get more capacity. This can be done by either increase service frequency. However increasing service frequency cannot be done easily always. At a certain frequency the operator namely increases the chanches of bus bunching which can causes inefficient operations and eventually lead to an unreliable service. What operators also mention. Increasing the service frequency means also adding more buses to the fleet and extra personnel. This cannot always be done easily.

Then the other option in order to increase capacity is insetad of increasing sevice frequency, increasing the vehicle capacity. With this solution the operator can increase capacity while not having to keep in mind that a bigger fleet is needed and more personnel is needed to operate.

5.1.2. Network Efficiency

A phenomenemn mentiond by both operator frequently is about the network efficiency which is reduced when articulated buses are deployed. Operating a mixed fleet of both articulated and standard buses can lead to reduced operational flexibility, as not all vehicle types can be deployed interchangeably on all routes. In practice, articulated buses remain assigned to specific routes throughout the day, with limited exchange between lines that are specifically adapted for their use. Deployment on regular lines is often not feasible due to too much excess capacity.

In order to limit these effects on network efficiency is when multiple lines in the network are deployed with articulated buses. HTM and GVB both have a balanced fleet, which means around the same number of articulated buses as well as conventional buses on around the same numbers of routes. This is largely due to the balanced composition of their fleets, which allows for effective distribution of vehicle types across the network. GVB additionally highlighted that a clear internal distinction is made between lines operated based on capacity needs (requiring articulated buses) and lines operated according to contractual frequency requirements (suitable for standard buses).

5.1.3. Electric or Fuel

Another important thing which was mentioned is wether to deploy electric articulated buses or fuel driven. If there is chosen for fuel driven the main advantage is that it is possible to drive almost the whole day and no additional fueling is necessary. However something that also is with fuel driven is that operating costs are higher as fuel is much more expensive. Also, for the operator is may not be nice to deploy the buses with fuel as in line with sustainability electricy is more the thing.

When deploying the articulated buses electric. A whole new trade-off arrises. Since the action radius of articulated buses is usually lower than that off the conventional electric bus, it needs too charge more often and for that, charging infrastrcuture is needed.

Both interviewed operator solved this by installing charging infrastructure at the start and end of a service line. GVB also has installed charging facilities at both termini of all articulated bus lines and supplemented this with additional charging points throughout the city, including major train stations.

The HTM also operates one line which does not have charging facilitities on the service line. If an operator chooses to not equip lines with charging infrastructure it means that the articulated buses on that line need to drive back to the depot and charge overthere. This is possible and can reduce investment costs however, it does mean that more buses are needed to operate on that line. It also means a lower network efficiency as more deadhead kilometers are driven. That is, kilometers driven in a bus without passengers.

For an operator they should check wether it is usefull to install charging facilties on the service line. If a line is close to its depot it namely maybe sufficient to do the charging overthere.

5.1.4. Infrastructure

Altough it depends on the type of articulated bus, the opeators indicated that the turning radius of an articulated bus being very similar to that of a conventional twelve-metre bus. This similarity is attributed to the shorter wheelbase of the front section. Depending on the specific design of the articulated bus, the rear section tends to follow the front section closely, ensuring that turning does not present significant difficulties.

Since no big difficulties arise, the articulated bus was for both operators fine to deploy in the network. Therefore it was not necessary to adapt lines. All the lines where articulated bus were going to be deployed was possible to also drive the bus.

Something which is important is that the bus stops maybe need to be adjusted. This also mainly depends on the requirements stataed by the muncipality and for example emergency services. This can lead to that the articulated bus is obliged to stop in a bus bay and that the existing bus bay may not to be rebuilt. This can lead to large investment costs and it can cost a lot of time and procedures.

5.1.5. Additional Benefits

In order to operate the articulated bus, no additional drivers license is required. However, it was indicated that some drivers were initially hesitant or nervous about the change.

To address this, drivers were given the opportunity to gain experience through additional instruction and supervised test runs. According to both operators, most drivers adapted quickly, and concerns typically disappeared after a few trips

Articulated buses offer benefits for temporary or ad hoc operations such as rail replacement services. HTM reported that where two or three standard buses were previously needed, a single articulated bus can now accommodate the same number of passengers, reducing operational complexity and staff requirements during such events.

The introduction of articulated buses has reduced or eliminated the need for reinforcement trips. HTM previously deployed additional standard buses on high-demand lines to cope with peak passenger loads. With the increased capacity of articulated buses, these extra services are no longer required, leading to improved resource efficiency

Both GVB and HTM reported that the transition to articulated buses required relatively little effort overall. While certain processes, such as infrastructure adjustments or operational planning, required extra attention, the rollout proceeded smoothly and without major obstacles. Both operators expressed satisfaction with the outcomes and believe that articulated buses enable them to offer a higher QoS quality to passengers.

5.2. Consideration Framework

Figure 5.3 shows the consideration framework based on the findings from the interviews with peer operators. Here the blue box indicates the main reason for the operator to consider to deploy articulated buses. The yellow eclipses then show the trade-offs they considered and the green boxes indicate their considerations.

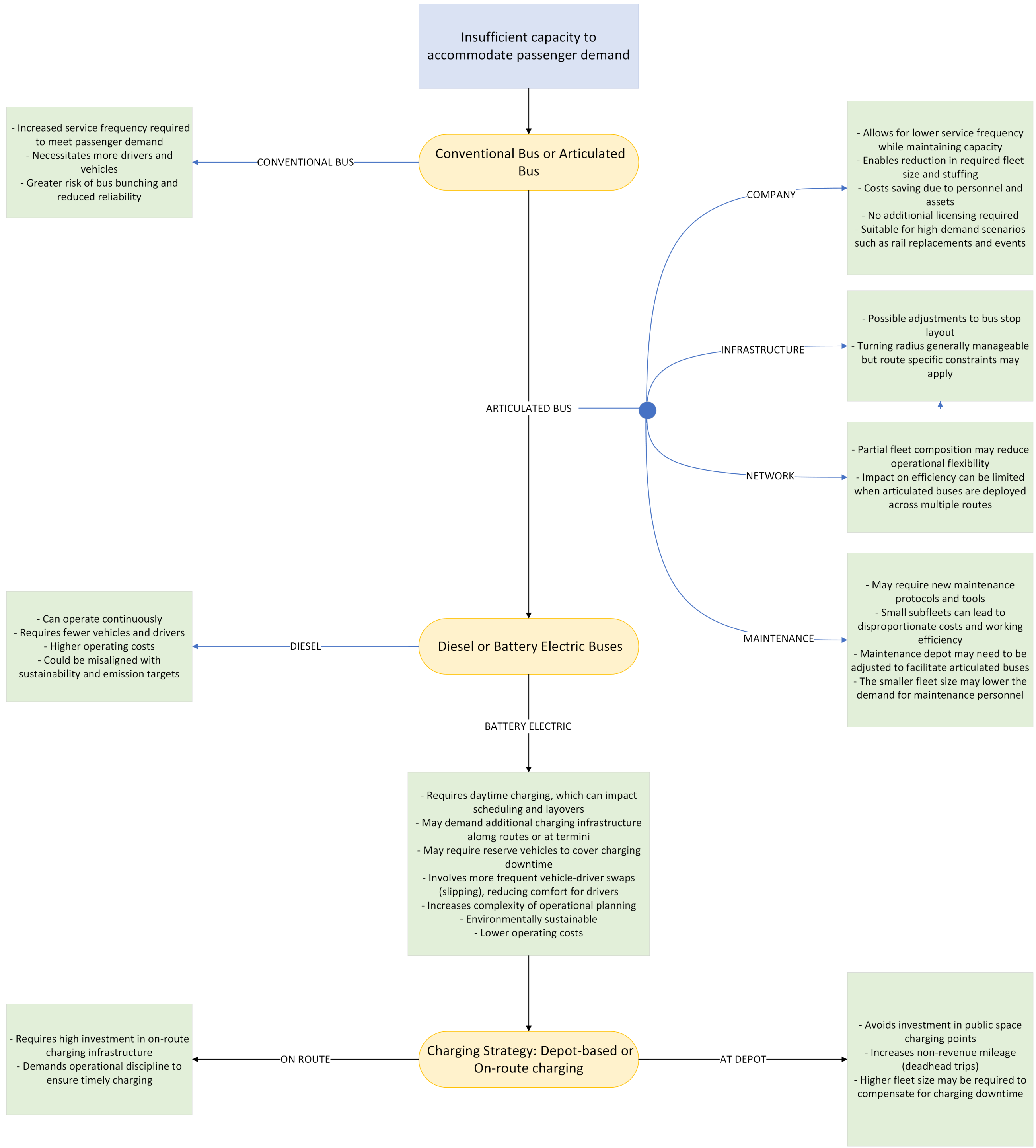


Figure 5.3: consideration Framework for deployment of Articulated Buses

6 Data-Analysis

This chapter introduces the case study of Rotterdam. A data analysis is performed using Automated Fare Collection (AFC) data in order to gain insight into the utilisation rates of public transport vehicles and to determine where, when, and to what extent crowding occurs and whether it presents operational challenges.

The analysis begins by examining the passenger distribution along a selected crowded service line, identifying the stops where ridership significantly increases. Subsequently, the hourly distribution of passengers on the same service line is investigated, revealing the time periods during which demand is particularly high. These initial steps provide an aggregated view of ridership patterns.

In the next stage, a more disaggregated analysis is carried out. The Level of Service (LoS), based on the passenger load per vehicle, is evaluated. This enables the identification of segments where passenger loads are excessive and may negatively affect network performance. Situations where crush capacity is reached, potentially resulting in denied boardings, are indicated with an 'F' rating.

The final step of the analysis involves repeating the LoS evaluation, this time assuming the deployment of articulated buses with higher capacity. This allows for the assessment of how the introduction of articulated vehicles could improve the Level of Service on the selected service line.

Eventually the aim of this chapter is to answer the following subquestion:

- *What is the current LoS on crowding and how could the use of articulated buses enhance this level?*

6.1. The data-set

The data set for the analysis is from week 45, November 2023. This data set was chosen on purpose, since OV-Pay was shortly introduced this moment. OV-Pay is not yet registered in the data and therefore making an analysis is less accurate. This doesn't mean OV-Pay was not used yet, but the share is much lower than more recent data. Tabel 6.1 shows which variables are present in the data set.

Variable	Description
businessday	Date of the transaction
siteid	ID of the location where the transaction takes place (corresponds with stationid)
msgreportdate	Time of the transaction
distancecovered	Distance traveled (only available at checkout)
entrystationid	Entry station ID (only available at check-out)
kaartnummer_hashed	Hashed (anonymized) card number
mediatype	Type of card (e.g., anonymous, personal, disposable)
modaltype	Type of transportation (2 = bus)
routeid	ID of the route
stationid	Station ID, matches siteid
transactiontype	Transaction type: 16 = check-in disposable card 30 = check-in with OV-chipcard, 31 = checkout OV-chipcard, 32 = check-in anonymous chipcard, 33 = check-out anonymous card, 36 = checkout disposable card
tripid	Trip number (specific identifier for the trip)
vehicleid	Vehicle ID number
tripnumber	Operational trip number
Distancecovered	Distance traveled (recorded only at checkout)
entrystationid	Entry station ID (station at check-in)
stationid	Station ID (corresponds with siteid)
transactiontype	Type of transaction: 30 = check-in OV chipcard, 31 = checkout OV-chipkaart, 32 = check-in disposable card, 33 = checkout disposable card

Table 6.1: Explanation of dataset variables

For this analysis the service lines 32,33,68 and 70 will be explored. These lines are frequently mentioned as crowded in interviews.

6.2. Processing of the data

The data will be processed according to a sequential plan, as shown in Figure 6.1.

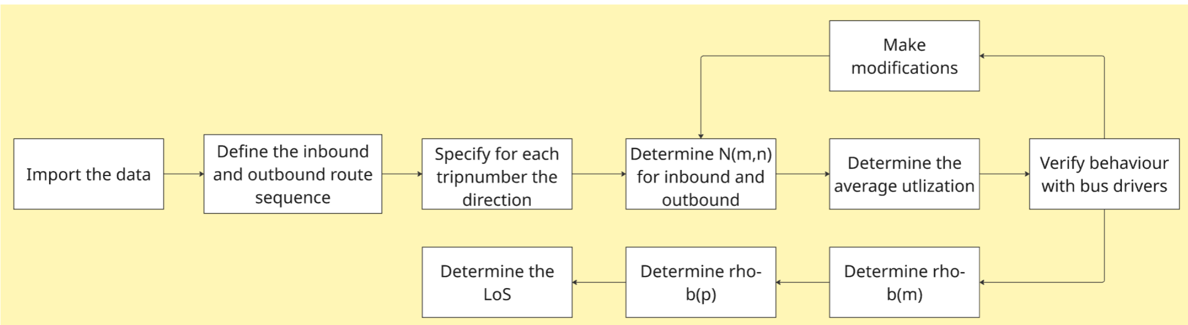


Figure 6.1: Sequence and Method for executing the Data-Analysis

First, the data is imported and filtered to include only the service line under investigation. For this service line, the next step involves specifying the route sequence for both inbound and outbound directions.

Once the route sequences have been defined, each trip (identified by trip number or trip ID) must be classified as either 'inbound' or 'outbound'. This classification is essential, as omitting it would lead to inaccuracies in identifying the number of passengers boarding and alighting.

Subsequently, using the values in the 'transactiontype' column and Equation 2.3, the stop-level occupancy for each direction (inbound and outbound) can be determined. This allows for the identification of occupancy patterns throughout the day and helps to pinpoint crowded stops.

Following this, passenger density is calculated using Equations 2.1 and 2.2 for defined time periods. In this analysis, hourly bins of one hour are applied. It is important to note that this approach provides the average passenger density over a given time interval, offering an aggregate view that highlights the peak hours for the service.

In the final step, the LoS for the service line is determined, providing a more disaggregated assessment. Using Equation 2.4, the LoS in relation to the load factor is calculated. The LoS thresholds are based on the TCQSM manual. In addition to load factor, the LoS is also assessed for service frequency. For the latter, no further data processing is required, as relevant reports are already available; however, the it still must be translated into corresponding LoS categories.

In order to account for OV-Pay users and fare evaders, a total correction factor of 8% has been applied in this analysis.

6.3. Serviceline 32

Figure 6.2 illustrates the current route of RET bus line 32. The route starts in Overschie, continues through Rotterdam West and the city centre, and terminates at Rotterdam Zuid Station. It comprises 26 stops over a total distance of approximately 11 kilometres, with an end-to-end travel time of around 40 minutes. Owing to its passage through central parts of the city, the route is also popular among tourists.

In comparison to its configuration in 2023, the current route includes a significant deviation: it now serves the Erasmus MC (Erasmus University Medical Center). The effects of this deviation are not accounted for in the present data analysis.

Figure 6.2: Route serviceline 32 (Moovit, 2025)

Figure 6.3 and 6.4 shows the average occupancy in week 45 for inbound and outbound. Based on the figures it is noticable that the occupancy has two peaks during the service. In the inbound direction, occupancy increases steadily from the starting point, with a pronounced rise in passenger numbers beginning around Persoonsdam and peaking at stops such as Willemswerf and Station Blaak. This trend likely reflects increased boarding in residential and suburban areas, with maximum passenger density occurring as the bus approaches the commercial and central zones of Rotterdam. A subsequent decrease in occupancy is observed after the peak, particularly beyond Mathenesserplein and Allard Piersonstraat, indicating passenger drop-offs as the bus continues into the northern segments of the city.

The outbound route shows a similar pattern in reverse, with occupancy rising steadily from Van Noortwijckstraat toward the city centre. Peak load conditions again occur around Station Blaak and Willemswerf, after which passenger numbers gradually decline as the bus travels southward. Notably, both directions show consistent patterns across different days, with minor fluctuations that may reflect daily variations in commuting behaviour or external factors such as weather or events.

These occupancy profiles suggest that the central part of the route is the most intensively used section, serving as a popular segment. The symmetrical nature of the patterns between inbound and outbound directions also indicates a well-balanced demand distribution, underscoring the strategic importance of line 32 in facilitating daily mobility across the city.

The occupancy patterns of bus line 32 reveal an unexpected trend when examining usage levels across the different days of the week. Typically, one might expect lower passenger volumes during weekends, particularly on Saturdays, due to reduced commuting activity. However, the data presented in the figures suggests otherwise. Specifically, Saturday 11 November (2023-11-11), shown in pink, consistently exhibits high occupancy levels in both inbound and outbound directions. In some cases, it even surpasses the average weekday usage.

A plausible explanation for this elevated Saturday occupancy could be the route's strong connection to the city centre, which attracts a high volume of leisure-oriented travel, including shopping, cultural visits, and tourism. Therefore, while weekday patterns reflect typical commuter behaviour which are marked by concentrated peaks around central business districts, the elevated ridership on Saturday points to the multifunctional role of line 32. It serves not only as a commuter line but also as an important connector for recreational and service-related activities, highlighting the diverse mobility needs it fulfils throughout the week.

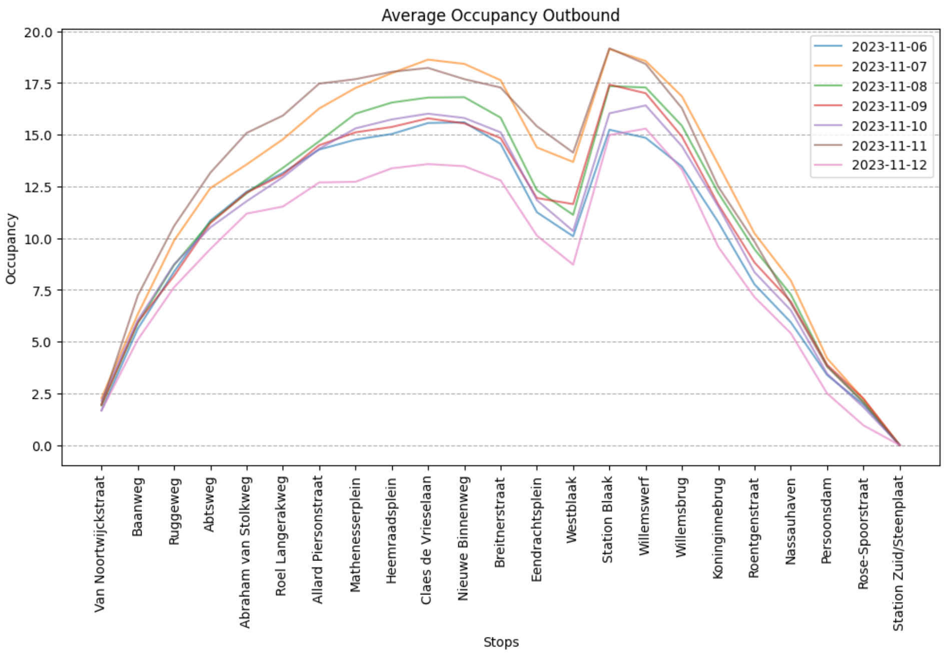


Figure 6.3: Passenger Distribution for Service Line 32 (Outbound)

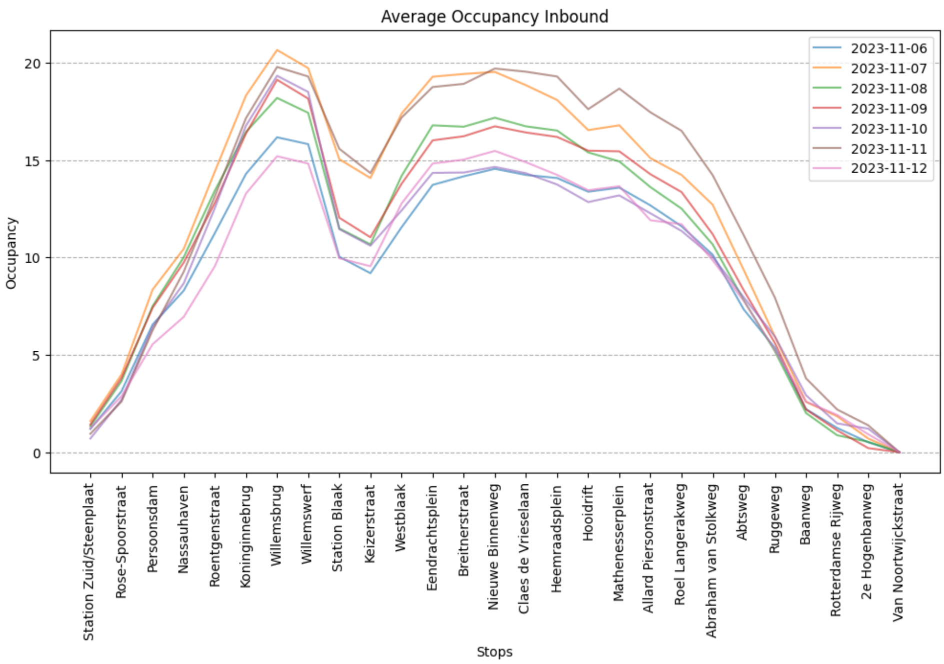


Figure 6.4: Passenger Distribution for Service line 32 (Inbound)

6.3.1. Passenger Density

Figure 6.5 shows the passenger density for the bus on serviceline 32 on tuesday 7 november.

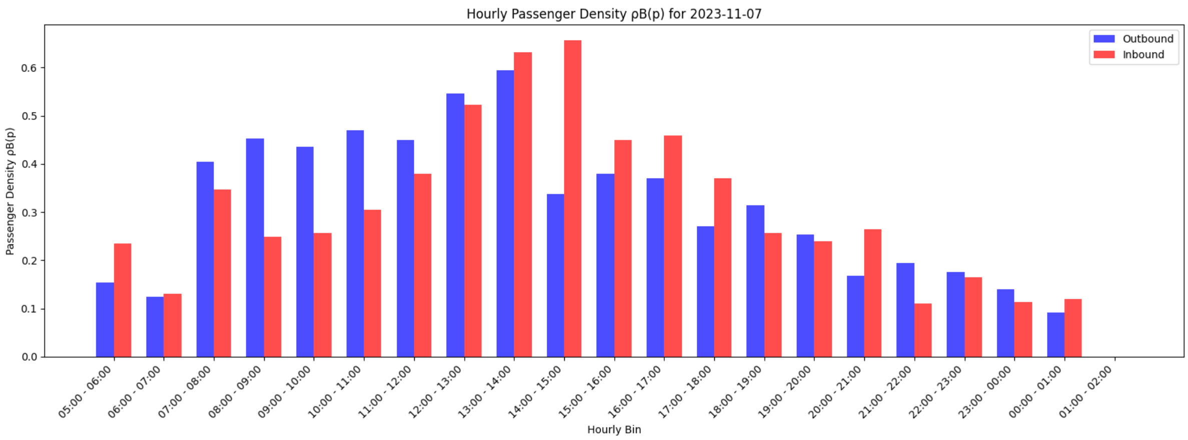


Figure 6.5: Hourly passenger density $\rho_B(p)$ for outbound and inbound bus trips on line 32

The day begins with relatively low passenger volumes in both directions. A moderate increase is observed in the inbound direction between 06:00 and 07:00. Between 08:00 and 11:00, the outbound direction shows consistently higher passenger density than the inbound direction.

From midday onwards, passenger densities increase in both directions. Between 12:00 and 17:00, sustained high occupancy is observed, with the inbound direction peaking between 14:00 and 15:00 (this is the highest value recorded throughout the day). The outbound direction also maintains elevated levels during this period, although less prominently.

After 18:00, a gradual decline in passenger density occurs in both directions. Around 21:00, a minor increase in inbound flow is visible, after which activity declines further. Post-22:00, minimal ridership is observed.

Overall, line 32 does not exhibit a traditional commuter profile with sharp peaks in the early morning and late afternoon. Instead, demand is more evenly distributed throughout the day, with a pronounced afternoon peak in the inbound direction.

6.3.2. Level of Service

Service Frequency

Between 06:00 and 09:00, the service operates with six vehicles per hour, corresponding to LoS B. This level of frequency is considered high-quality and generally allows for minimal waiting times, although passengers are more likely to consult schedules.

Between 09:00 and 15:30, the frequency decreases to four vehicles per hour, which places the service in LoS category C. This level indicates that passengers may experience longer intervals between buses and potentially less flexibility in travel planning, though the service remains within acceptable comfort and usability thresholds.

From 15:30 to 18:30, the frequency increases again to six vehicles per hour, resulting in a return to LoS B. This suggests that the service is aligned with increased afternoon demand, maintaining an adequate level of availability. During the evening period from 18:30 to 01:00, the frequency drops to two vehicles per hour, which corresponds to LoS D. At this level, the service becomes less attractive for choice riders and may require more deliberate trip planning, particularly in the context of reduced late-evening travel options.

Table 6.2: Service Frequency Levels of Service (LoS) for Bus Line 32

Time period	Vehicles/hour	LoS Category
06:00–09:00	6	B
09:00–15:30	4	C
15:30–18:30	6	B
18:30–01:00	2	D

Load Factor

The LoS distribution for bus line 32 on 7 November 2023 reveals substantial variation in occupancy across the day, with notable differences between the inbound and outbound directions. The outbound direction displays more fluctuation in LoS categories, especially during the late morning and early afternoon hours.

Between 05:00 and 07:00, both directions are characterised by low passenger loads, with LoS A being the predominant category. As the morning progresses (07:00–10:00), occupancy levels increase in both directions. Outbound trips during this period exhibit a mix of LoS B, C, and D, and small but recurring shares of LoS E. Inbound trips also show a rise in density, though LoS A remains more prominent, accompanied primarily by LoS B and C.

In the hours between 10:00 and 15:00, outbound services show a continued shift towards higher occupancy. LoS C and D become more dominant, while LoS E and F are also present in some intervals, particularly around 13:00–14:00. Inbound services follow a similar pattern but with fewer occurrences of LoS F and a relatively stronger presence of LoS A and B.

From 15:00 to 18:00, occupancy begins to decline gradually. Outbound trips still include LoS B through D, though the share of LoS A increases. In the inbound direction, a clearer return to lower density is observed, with LoS A and B dominating most intervals.

Evening and late-night hours (18:00–01:00) are marked by consistently low occupancy levels in both directions, with LoS A accounting for the vast majority of observations and only minor appearances of LoS B or C.

Figure 6.6: LoS distribution for Service Line 32 (Outbound)

6.4. Serviceline 33

Figure 6.7 presents the route of service line 33. This bus line connects Rotterdam Central Station with Metro Station Meijersplein, passing via Rotterdam The Hague Airport. The route includes 18 stops over a total distance of approximately 8.6 kilometres and has an end-to-end travel time of around 26 minutes. Line 33 serves a diverse group of passengers, including employees working in the northern parts of Rotterdam, high school students commuting to and from school, and air travellers who use the service to conveniently connect the airport with the city centre.

Figure 6.7: Route serviceline 33 (Moovit, 2025)

In the outbound direction (Figure 6.8), which connects Rotterdam Central Station to the northern residential and peripheral areas, the data reveals a clear and consistent pattern of decreasing occupancy over the route. Occupancy peaks at the beginning of the line, particularly at Rotterdam Centraal and Blijdorp Metro, with average values exceeding 20 passengers during weekdays. These central stops act as primary boarding points, capturing high demand likely related to commuting and trasnfers from other transport modes. The subsequent stops show a gradual yet sustained decrease in occupancy, as passengers disembark along the way. Beyond Hoornweg and through the middle section of the route—2e Hoogebaanweg, De Lugt, West-Sidelinge—the passenger load continues to diminish. The final stretch of the outbound route, from Burgermeester Bosstraat to Gatwickbaan features notably low occupancy. During weekdays a noteable trend is observable that utlisation increases again from about Rotterdam Airport Lutonbaan. This behaviour could be caused by the fact that around the airpots offices are located and people are heading to the terminate stop where the Metro is also located.

Weekend days, display lower overall occupancy throughout the entire outbound route. The decline in ridership is more moderate, and the initial loading levels are reduced compared to weekdays, suggesting a shift in the purpose of travel—from structured commuting patterns during the workweek to more dispersed, possibly leisure-related travel over the weekend.

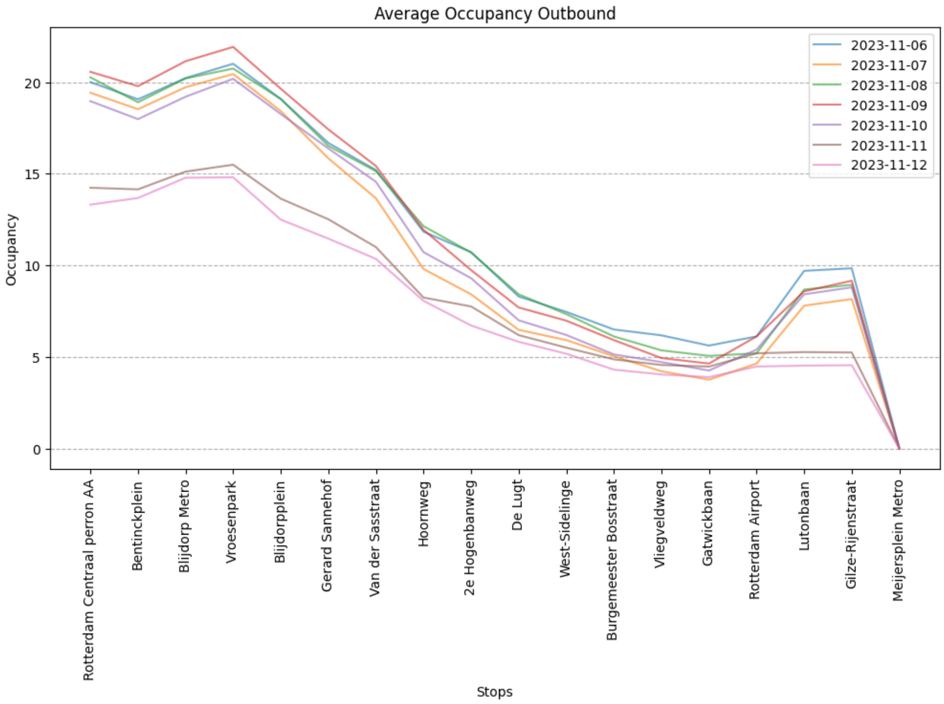


Figure 6.8: Passenger Distribution for Service Line 33 (Outbound)

In the inbound direction (Figure 6.9), the pattern is reversed and similarly reflects the commuter flow into the city. Initial occupancy levels at Meijersplein Metro and Glize-Rijnstraat are relatively low, typically between 2 and 6 passengers. After a brief dip around Lutonbaan and Rotterdam Airport, occupancy begins to rise, increasing significantly between Burgemeester Bosstraat and Hoornweg. This central section of the route experiences the most substantial growth in passenger numbers, with average occupancy peaking around Blijdorpplein. From there, occupancy remains high up to the terminal stop, Rotterdam Centraal, although some passengers disembark at Blijdorp Metro.

As with the outbound direction, the inbound weekday data indicates a structured commuter pattern. The curves for 6–10 November follow a consistent trajectory with only minor deviations in peak levels, highlighting the regularity of weekday travel behaviour. In contrast, weekend days exhibit markedly lower occupancy, with gentler gradients—particularly on Sundays—and fewer pronounced peaks, reflecting a significant drop in traditional work-bound commuter flow. Notably, the dip in occupancy around Rotterdam Airport observed on weekdays is absent during the weekend, suggesting that this section is primarily used by weekday commuters.

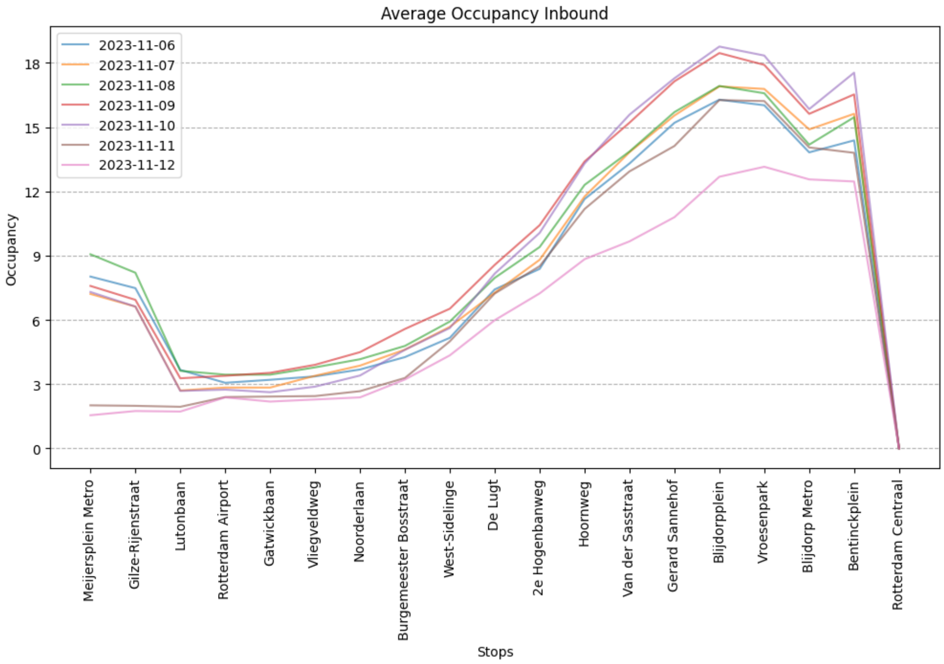


Figure 6.9: Passenger Distribution for Service Line 33 (Inbound)

6.4.1. Passenger Density

Figure 6.10 shows the passenger density for the bus on serviceline 33 on tuesday 7 november.

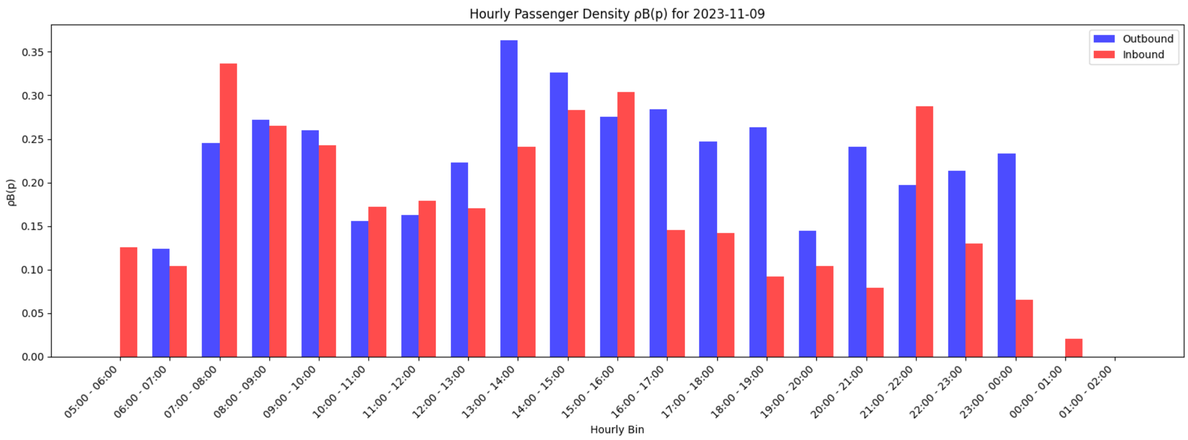


Figure 6.10: Hourly passenger density $\rho_B(p)$ for outbound and inbound bus trips on line 33

In the inbound direction, the highest density is recorded between 08:00 and 09:00, indicating a peak in morning passenger activity. Following this, the density remains moderate throughout the midday period. A secondary increase occurs between 15:00 and 16:00, followed by a notable rise between 21:00 and 22:00, reaching just below 0.29. After 22:00, the density rapidly declines and is near zero after midnight.

In the outbound direction, the density is more evenly distributed over the day, with no single dominant peak. The highest density occurs between 13:00 and 14:00, slightly higher than the peak in the inbound direction. Elevated densities are also observed between 14:00 and 17:00, where values remain above 0.28. The density stays relatively stable between 10:00 and 19:00, indicating sustained outbound demand in the afternoon hours. After 20:00, the density gradually decreases, with low values recorded after midnight.

6.4.2. Level of Service

Service Frequency

Between 06:00 and 18:30, the line operates with four vehicles per hour. According to the headway-based LoS framework, this corresponds to LoS category C. This level is generally considered acceptable, offering a reasonable wait time for most passengers.

In the evening period, from 18:30 to 01:00, the frequency decreases to two vehicles per hour, which results in a LoS D classification. At this level, the service becomes less attractive for riders who have alternative travel options and may require increased schedule adherence from passengers.

Table 6.3: Service Frequency Levels of Service (LoS) for Bus Line 33

Time period	Vehicles/hour	LoS Category
06:00–09:00	4	C
09:00–15:30	4	C
15:30–18:30	4	C
18:30–01:00	2	D

Load Factor

The LoS distribution for bus line 33 on 9 November 2023 indicates modest variations in occupancy throughout the day, with observable differences between the inbound and outbound directions. The outbound direction exhibits a broader spread across LoS categories, particularly during the midday and early evening periods.

During the early morning hours (05:00–07:00), both directions are characterised by low occupancy levels, as reflected in the overwhelming presence of LoS A. Between 07:00 and 10:00, occupancy increases noticeably. In the outbound direction, this period shows a more diverse LoS profile, with LoS B and C accounting for significant portions of the distribution and smaller shares of LoS D and E also present. Between 08:00 and 09:00 a small portion also is classified as level F, which indicates that the crush capacity is reached. The inbound direction during this time exhibits a slightly more uniform pattern, though instances of LoS D and even F are still observed, particularly around 08:00. This indicates a clear morning peak in both directions, with increased pressure on available capacity.

Between 10:00 and 15:00, a sustained mix of LoS levels is visible. In the outbound direction, LoS A gradually declines while LoS B and C become more dominant. LoS D appears in several time intervals, and LoS E is present in limited cases, suggesting moments of higher onboard density. Inbound trips during this period show relatively higher shares of LoS A, but still include LoS C and D in most hours, especially between 13:00 and 15:00.

From 15:00 to 18:00, outbound services maintain moderate congestion, with LoS B through D occurring frequently. Passenger volumes remain relatively high, but without indications of consistent overcrowding. The inbound direction shows a gradual decline in load, with LoS A becoming dominant again by the end of the peak period.

During the evening and night-time hours (18:00–01:00), both directions are characterised by low occupancy levels. LoS A dominates across all intervals, and higher-density categories are no longer observed. This suggests that during this period there is sufficient capacity to meet demand.

Figure 6.11: LoS distribution for Service Line 33 (Outbound)

6.5. Serviceline 68

Figure 6.12 presents the route of service line 68, which operates between Zuidplein and Heijplaat RDM Campus. The route comprises 14 stops distributed over a distance of 8 kilometres, with an end-to-end journey time of approximately 20 minutes. One of the stops along this route is 'Anthony Fokkerweg', which serves several nearby secondary schools. Due to the high demand from schoolchildren, a supplementary service has been introduced that operates solely between Zuidplein and Anthony Fokkerweg, via Slinge Metro.

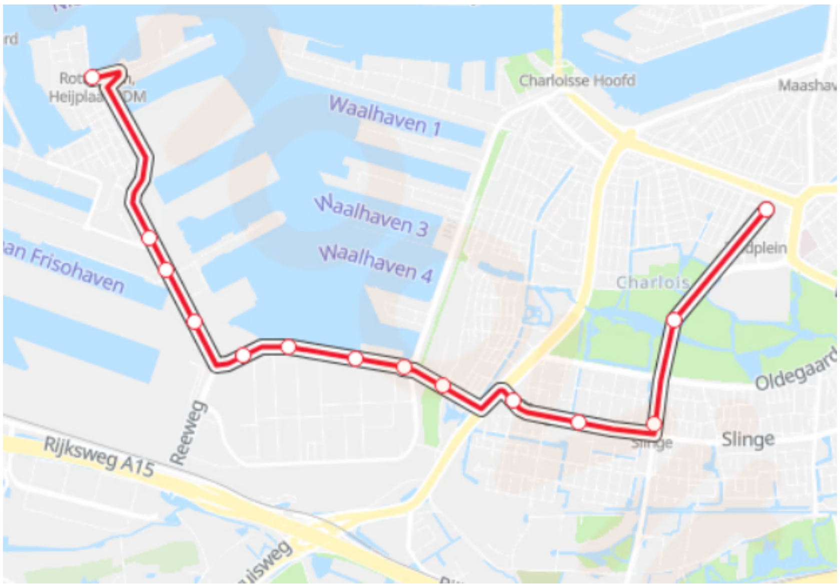


Figure 6.12: Route serviceline 68 (Moovit, 2025)

The outbound travel pattern (Figure 6.13) of service line 68, operating from Zuidplein to RDM Campus, demonstrates a pronounced peak in passenger activity at the early stages of the route. A steep rise in occupancy is observed shortly after departure, particularly at major stops where interchange with other lines occurs. It is suggested that the outbound flow is primarily driven by morning commuters and school-related traffic boarding at Zuidplein and its immediate surroundings. Following this initial increase, occupancy gradually declines as the bus continues its route, with many passengers alighting around mid-route stops such as Anthony Fokkerweg and Plein 1953. After this segment, the remaining part of the route towards RDM Campus experiences relatively low occupancy levels, indicating limited boarding and alighting activity in these areas. The overall trend highlights the central segment of the route as the most intensively used during outbound operations.

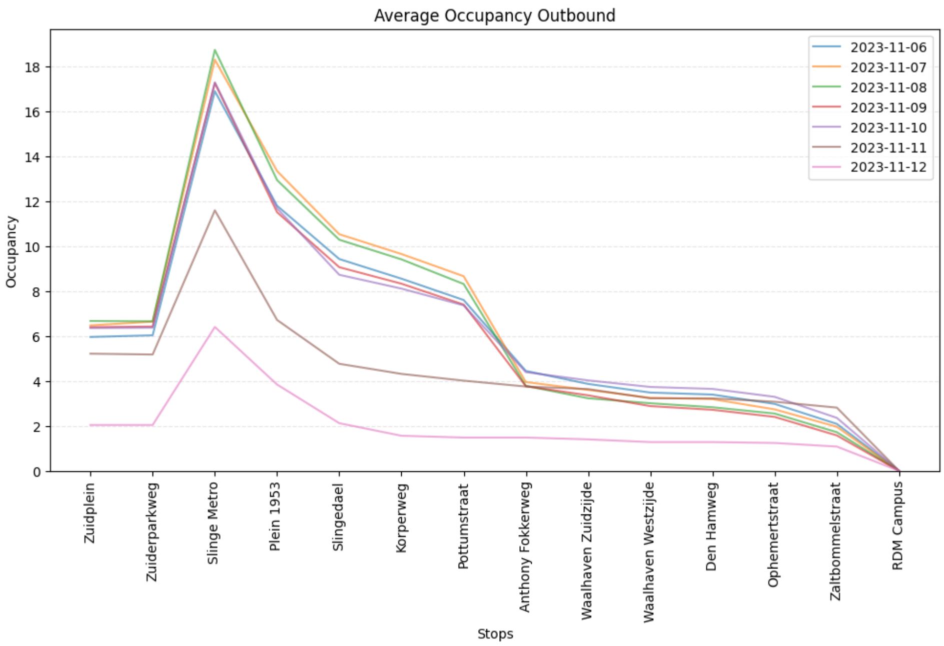


Figure 6.13: Passenger Distribution for Service line 68 (Outbound)

In the inbound direction (Figure 6.14), travelling from RDM Campus to Zuidplein, the occupancy profile displays a more gradual build-up. The route begins with low passenger numbers, reflecting relatively limited activity in the peripheral areas. As the bus approaches the mid-section of the route, particularly near stops serving educational institutions, occupancy levels increase substantially. This pattern suggests that the inbound service plays a key role in transporting students and other passengers towards central urban areas. After peaking around the same segment where outbound occupancy declines, the inbound service also experiences a rapid drop in passenger numbers, as most travellers disembark before reaching Zuidplein. This inverse flow underlines the importance of specific mid-route locations as both origin and destination hubs, depending on the direction of travel, and supports operational strategies that focus on optimising capacity along this critical segment of the route.

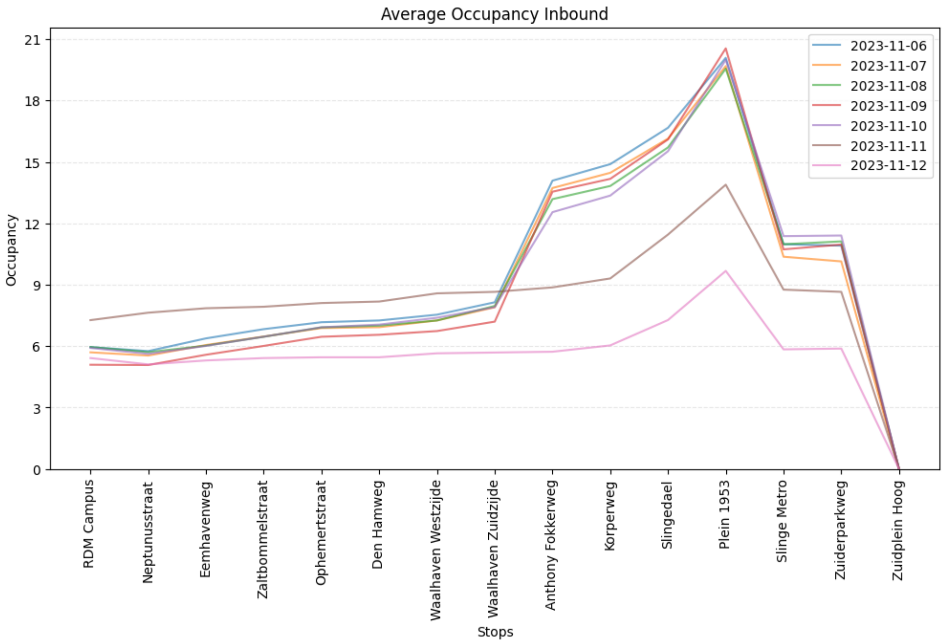
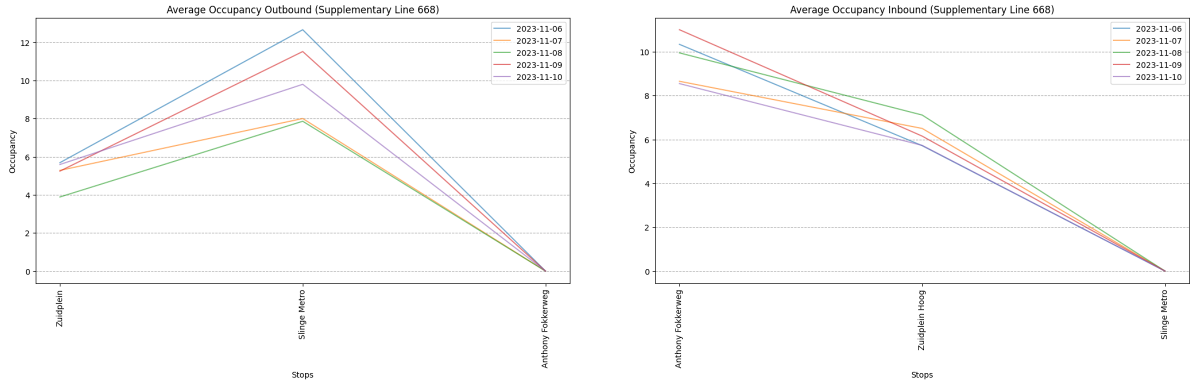


Figure 6.14: Passenger Distribution for Service line 68 (Inbound)

Supplementary Line 668

In the outbound direction, the occupancy increases notably between Zuidplein and Slinge Metro, reaching its peak consistently at Slinge Metro. After Slinge Metro, the occupancy declines sharply towards Anthony Fokkerweg, where all passengers disembark. This pattern corresponds with the expected end-of-line correction, where the occupancy is set to zero at the final stop. Although the absolute number of passengers varies per day, the shape of the profile remains stable, characterised by a build-up followed by a clear decline.

In the inbound direction, trips begin with a relatively high occupancy at Anthony Fokkerweg. The occupancy then gradually decreases along the route, with a marked reduction at Zuidplein Hoog, and continues to decline to zero at Slinge Metro. These patterns remains consistent for inbound and outbound throughout the observed days.



(a) Outbound direction of line 668.

(b) Inbound direction of line 668.

Figure 6.15: Route segments of line 668 shown in outbound (a) and inbound (b) direction.

6.5.1. Passenger density

Figure 6.16 shows the passenger density for the bus on serviceline 33 on Thursday 9 november.

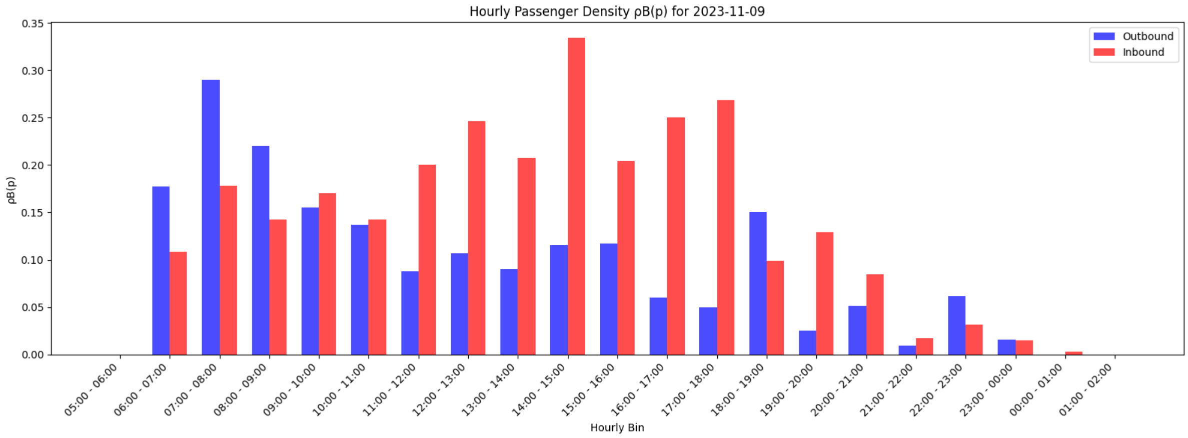


Figure 6.16: Hourly passenger density $\rho_B(p)$ for outbound and inbound bus trips on line 68

The outbound direction shows the highest passenger density during the morning hours, particularly between 07:00 and 09:00, peaking around 08:00. This indicates that most outbound trips during this timeframe experience substantial occupancy. After 09:00, the outbound density gradually decreases, with relatively low values observed for the remainder of the day.

In contrast, the inbound direction exhibits a clear increase in passenger density from 12:00 onwards, reaching its maximum between 15:00 and 18:00. During this afternoon period, the inbound density surpasses the outbound direction significantly, suggesting sustained high passenger loads. The highest peak occurs around 15:00, followed by persistently elevated density until 18:00, after which a steady decline is observed.

This asymmetric occupancy pattern may be explained by the high concentration of students travelling to school in the morning, resulting in a sharp peak in passenger volume during those hours. Their return journeys, however, tend to be more dispersed throughout the day, leading to a flatter occupancy distribution in the afternoon. Additionally, the presence of reinforcement services provided by a supplementary line during the morning peak likely contributes to a more even distribution of passenger demand across multiple vehicles. In contrast, during midday hours, the supplementary line operates less frequently, which may result in a higher load on fewer vehicles.

6.5.2. Level of Service

Service Frequency

From 06:00 to 18:30, the line operates with six vehicles per hour, which corresponds to Level of Service (LoS) category B. This level reflects frequent and reliable service that allows passengers to plan trips with minimal reliance on schedules, while still offering good accessibility.

Between 18:30 and 01:00, the frequency is reduced to two vehicles per hour. This shift corresponds to LoS D, which represents a lower service standard. At this level, the service may become less appealing for non-captive riders and could lead to longer wait times for evening travellers.

The supplementary line 668 is not incorporated in this analysis, as its frequency of operation varies and is not consistently documented.

Table 6.4: Service Frequency Levels of Service (LoS) for Bus Line 68

Time period	Vehicles/hour	LoS Category
06:00–09:00	6	B
09:00–15:30	6	B
15:30–18:30	6	B
18:30–01:00	2	D

Load Factor

For line 68 due to its assymetric occupancy both outbound (Figure 6.17 and inbound (Figure 6.18) LoS will be analysed seperately.

In the outbound direction, it is noticeable that capacity issues arise between 07:00 and 09:00. During this time window, the LoS drops to level F, indicating that the service operates at crush capacity, with a heightened risk of denied boardings. After this peak period, no major capacity issues appear to persist in the outbound direction. Although minor occurrences of level D are observed throughout the day, the service predominantly operates at level A, with occasional instances of levels B and C.

Regarding the inbound direction, capacity issues begin to emerge around 12:00. Between 12:00 and 18:00, Level F is reached almost structurally, accompanied by other lower LoS levels, indicating sustained overcrowding and potential operational strain. After 18:00, these capacity issues subside, and the service predominantly operates at Level A, with only minor occurrences of Levels B and C.

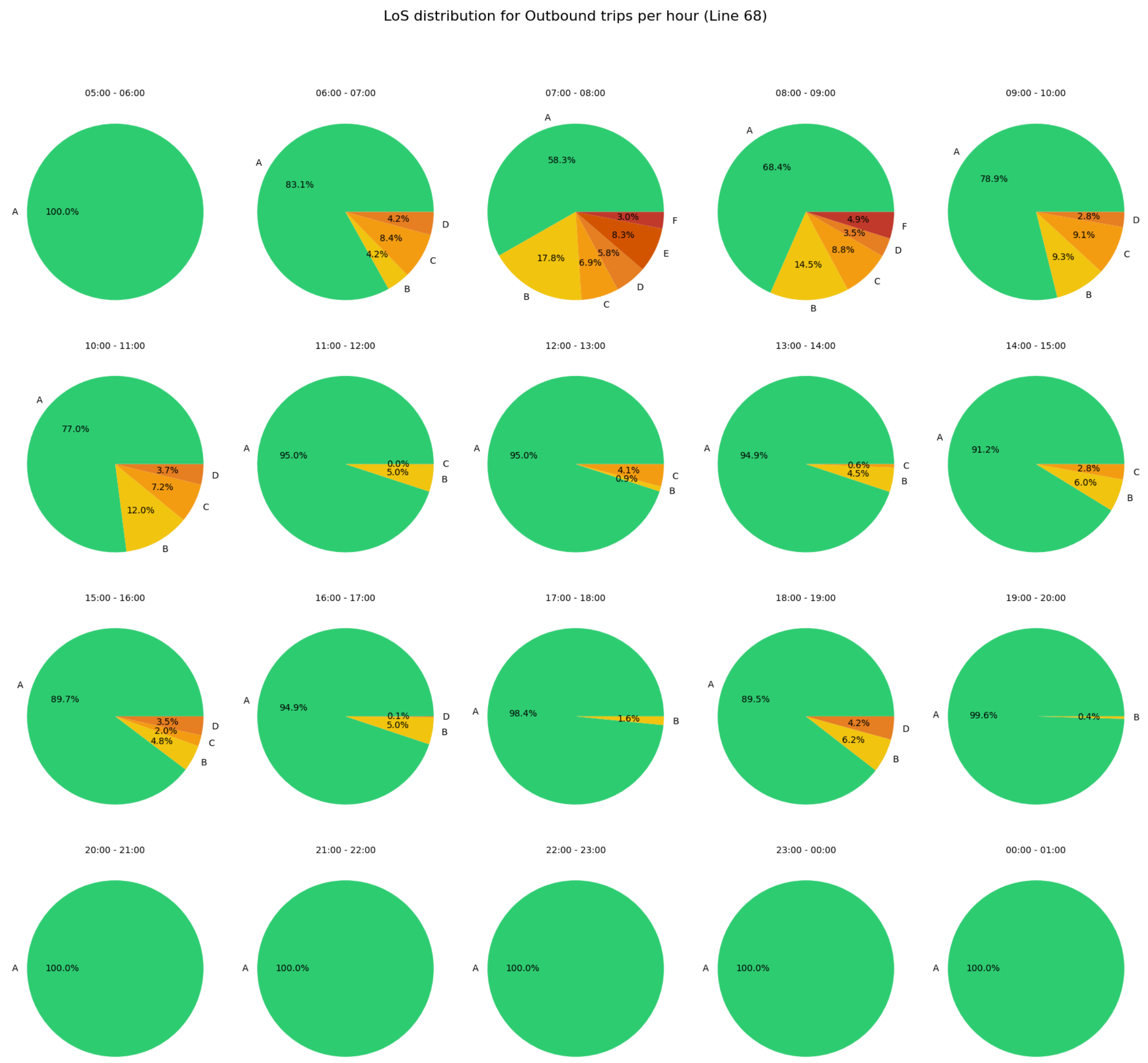


Figure 6.17: LoS distribution for Service Line 68 (Outbound)

Figure 6.18: LoS distribution for Service Line 68 (Inbound)

6.6. Serviceline 70

Lastly, bus service line 70 is analysed. This line operates entirely within the southern part of Rotterdam and runs bi-directionally between Garage Sluisjesdijk and Keizerswaard. The total route spans approximately 11.5 kilometres and includes 26 stops, with a full one-way trip taking around 39 minutes. In addition to serving several high schools, the route passes through densely populated neighbourhoods and key transfer points, which contributes to its high level of usage and importance within the network.

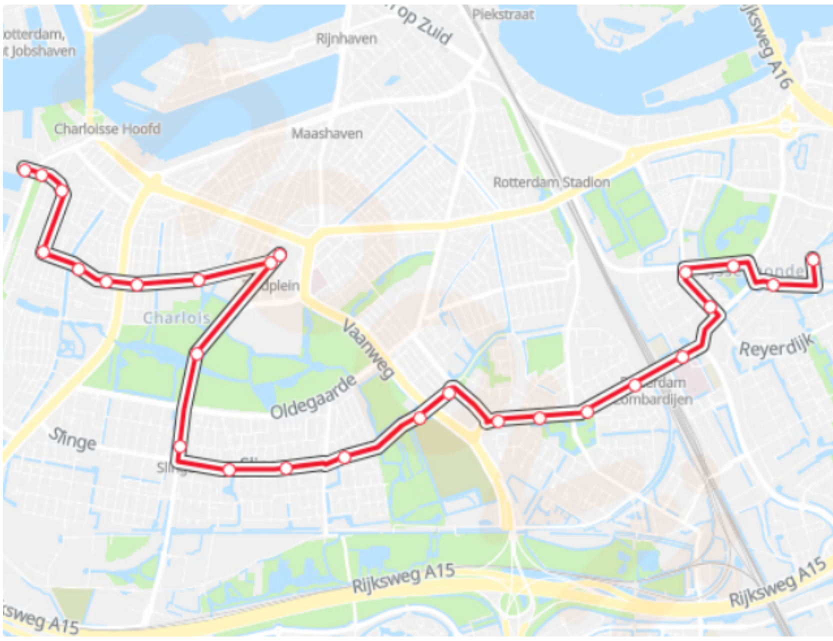


Figure 6.19: Route serviceline 70 (Moovit, 2025)

In the outbound direction, which starts at Garage Sluisjesdijk and proceeds towards Keizerswaard, passenger boarding begins at Waalhaven N.Z. Shortly after, occupancy increases sharply, reaching the first and highest peak of the outbound route at Carnissesingel. At Zuidplein, a major transfer hub within the RET network, a substantial number of passengers alight, resulting in a temporary decrease in occupancy. The second peak occurs shortly thereafter at Slinge Metro, another key interchange. From this point onward, occupancy gradually declines as the bus approaches its final destination. During weekends, the occupancy curve appears notably flatter, with significantly lower peak values. The dual-peak pattern remains visible, though less pronounced.

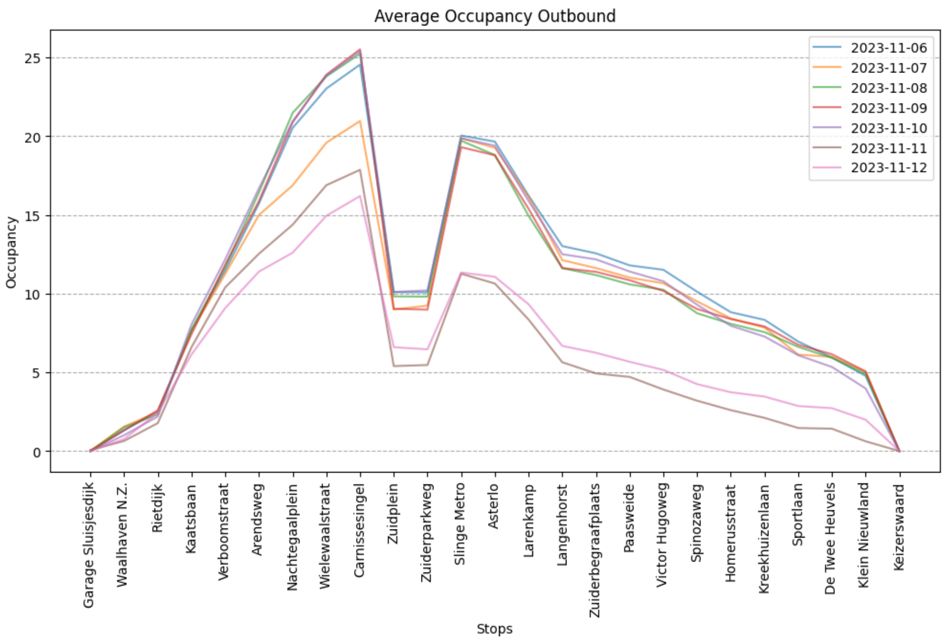


Figure 6.20: Passenger Distribution for Service line 70 (Outbound)

In the inbound direction, the pattern reverses, with occupancy gradually increasing as the route approaches Slinge Metro. The route begins with moderate demand between Keizerswaard and Zuiderbegraafplaats, followed by a steady build-up. Between Langenhorst and Asterlo, a sharper increase sets in, culminating in a broad peak around Larenkamp. Then, the dip follows as soon as the bus approaches Slinge Metro, after which occupancy remains relatively stable but lower, indicating that many passengers alight at the metro connection or adjacent hubs. At Zuidplein, a significant increase in passenger numbers is observed which is opposite to the pattern seen in the outbound direction. The remainder of the route, from Carnissesingel to Garage Sluisjesdijk, exhibits a consistent drop-off pattern as the vehicle approaches the terminus.

Weekday occupancy profiles display strong consistency, showing nearly identical trends with variations primarily in peak intensity. Weekend ridership is considerably lower, particularly on Sundays, where both the rate of increase and peak levels are substantially reduced.

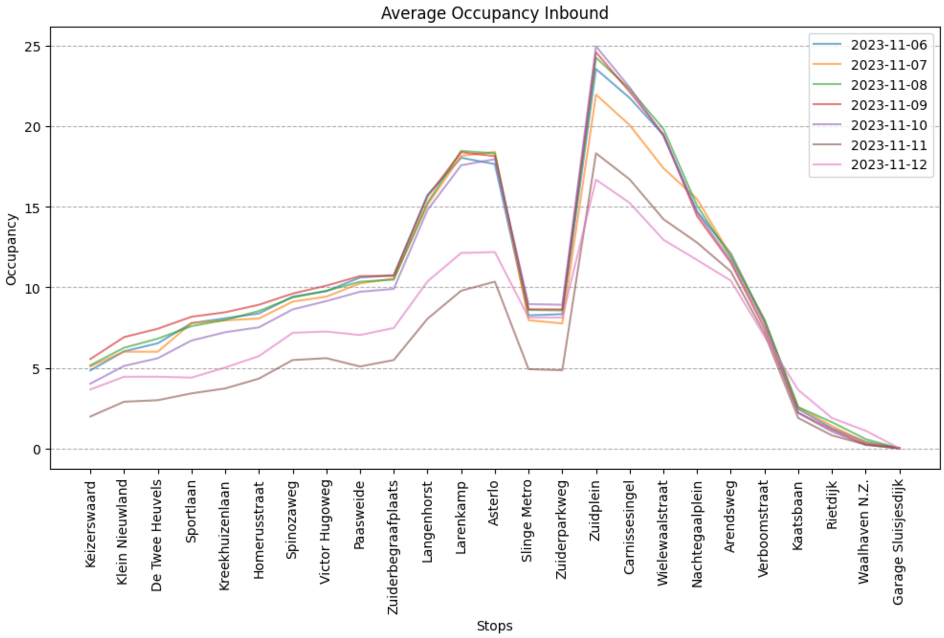


Figure 6.21: Passenger Distribution for Service line 32 Inbound

6.6.1. Passenger density

Figure 6.22 shows the passenger density for the bus on serviceline 70 on Thursday 9 november.

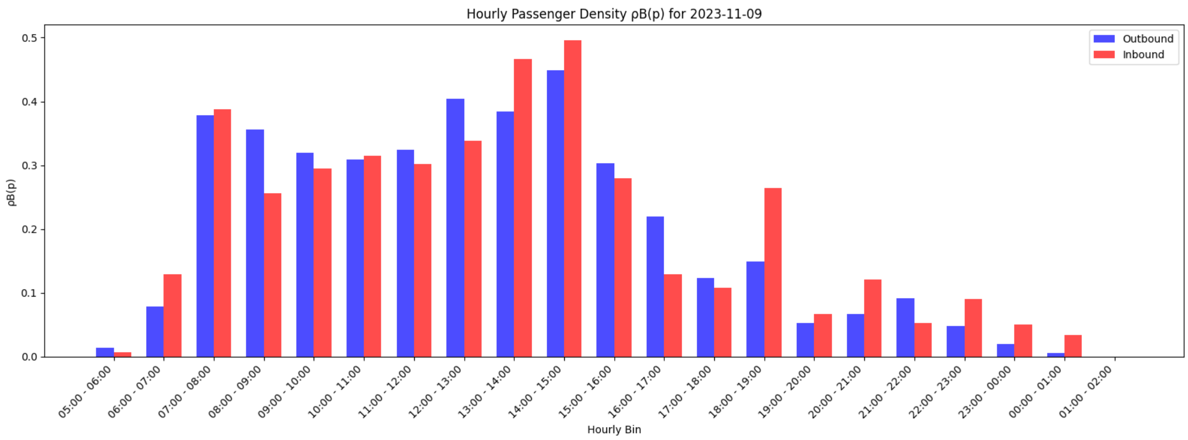


Figure 6.22: Hourly passenger density $\rho_B(p)$ for outbound and inbound bus trips on line 70

During the early morning period (05:00–07:00), passenger densities remain low in both directions, reflecting limited demand prior to the main commuting hours. A pronounced increase follows from 07:00, peaking between 07:00 and 08:00, which aligns with typical weekday morning travel patterns. Outbound services exhibit slightly higher density levels than inbound ones during this interval. After the peak, densities decline moderately yet remain elevated through the late morning and early afternoon (10:00–14:00).

From 12:00 onwards, a second increase in $\rho_B(p)$ is observed, culminating in a secondary peak between 14:00 and 15:00. During this period, inbound services show comparable or even higher densities than outbound ones, potentially due to return trips from schools or part-time employment. After 15:00, occupancy densities steadily decline in both directions, indicating a tapering of demand towards the evening.

Overall, the data indicate a bimodal distribution in bus occupancy, with morning and afternoon peaks accompanied by relatively high attractiveness throughout the entire day.

6.6.2. Level of Service

Service Frequency

Between 06:00 and 09:00, the line operates with a frequency of eight vehicles per hour, corresponding to LoS A. This indicates very frequent service where passengers generally do not need to rely on schedules. A slightly lower frequency is observed between 09:00 and 15:30, with six vehicles per hour, placing the service in LoS B. This still reflects a high-quality level of service, though passengers are more likely to consult schedules.

From 15:30 to 18:30, the frequency increases again to eight vehicles per hour, returning to LoS A. In the evening period, between 18:30 and 01:00, the frequency drops to three vehicles per hour. This corresponds to LoS C, representing the maximum desirable waiting time for passengers who miss a bus.

Table 6.5: Service Frequency LoS for Bus Line 70

Time period	Vehicles/hour	LoS Category
06:00–09:00	8	A
09:00–15:30	6	B
15:30–18:30	8	A
18:30–01:00	3	C

Load Factor

Figure 6.23 shows the LoS distribution for the outbound for bus line 70 on 9 November 2023. The distribution for the inbound and outbound are very similar, tough outbound is a bit more occupied.

During the early morning hours (05:00–07:00), outbound trips were predominantly characterised by LoS A. This trend changes markedly from 07:00 to 09:00, where a more heterogeneous LoS pattern emerges. In this morning peak, higher LoS categories such as C, D, E, and F become increasingly visible. From 09:00 to 11:00 then it cursh load don't appear but shortly after this happens again from 12:00 to 17:00 the crush load is structurally met and other low quilities become increasingly visible. From 17:00 onward, occupancy levels drop noticeably, and by the evening hours (20:00–01:00), almost all trips are categorised under LoS A. This suggests that service supply during off-peak hours remains comfortably within capacity limits.

The inbound direction shows broadly similar temporal trends but with slightly lower crowding levels overall. Morning peak periods still exhibit elevated occupancy, with LoS C, D, and E present, and even isolated instances of LoS F. However, the relative share of LoS A remains higher than in the outbound direction during peak hours. In the afternoon and evening periods, inbound trips increasingly shift to LoS A and B, with only minimal indications of capacity strain. From 20:00 onwards, the LoS profile in both directions is nearly identical, showing consistently low occupancy.

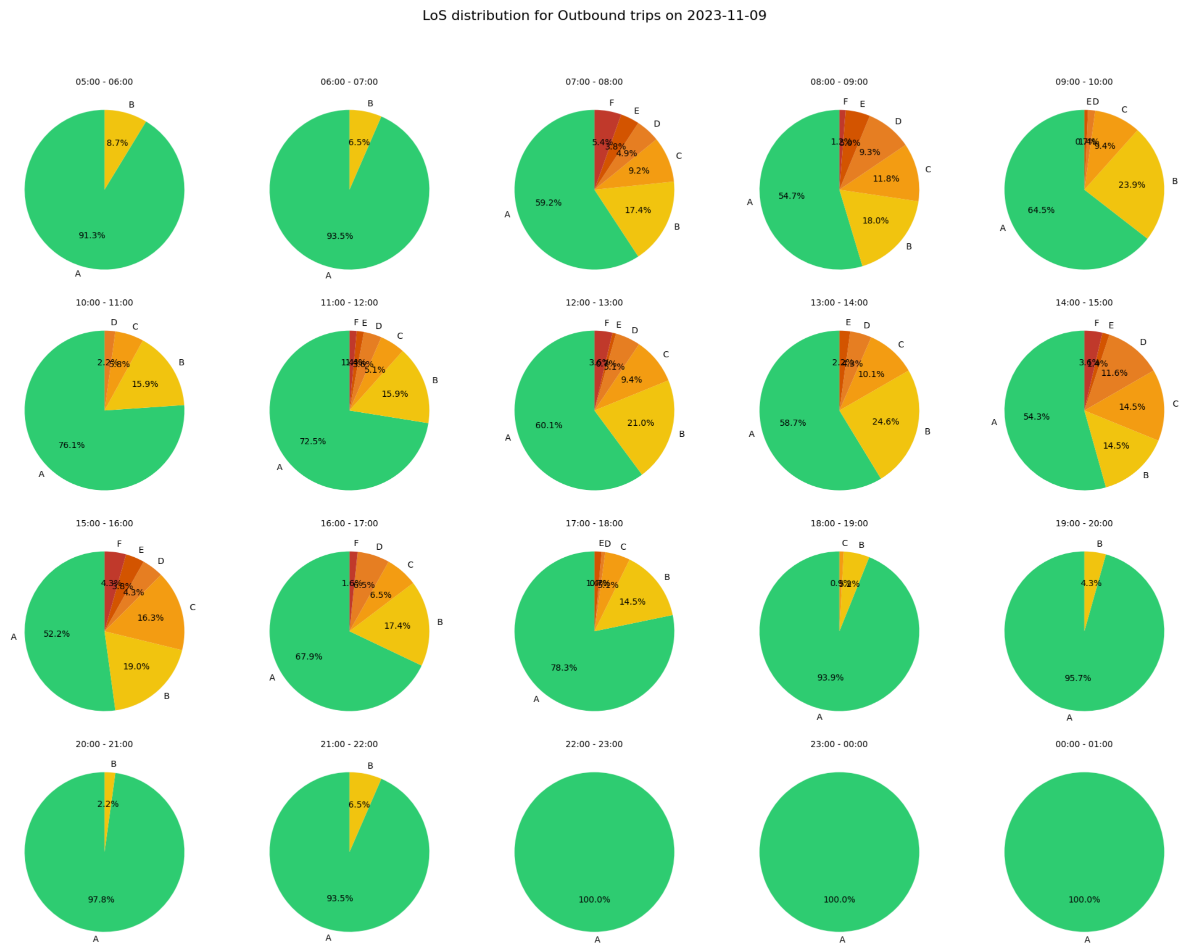


Figure 6.23: LoS distribution for Service Line 70 (Outbound)

6.7. LoS with Articulated Bus Capacity

The tables below present the results of the data analysis. In this analysis, vehicle capacity has been increased to assess the impact of articulated buses on the LoS. Whereas conventional buses were modelled with a seating capacity of 35, this has been raised to 60 to simulate the potential effects of deploying articulated vehicles. The analysis assumes unchanged service frequency and passenger demand, without accounting for denied boardings.

6.7.1. Service line 32

In the outbound direction, the vehicle capacity of articulated buses resulted in a substantial increase in the proportion of rides operating under LoS A across all time periods. During the morning peak, the share of LoS A increased from 45.5% to 91.3%, while LoS B decreased from 22.7% to 8.7%. All higher crowding levels (LoS C to F), which collectively represented 31.9% in the conventional scenario, were reduced to 0.0% when articulated buses were used. Similar trends are observed during the midday period, where the share of LoS A increased from 35.9% to 89.8%, and the share of LoS D to F decreased from a combined 10.1% to 0.0%. During the evening peak, LoS A rose from 62.8% to 96.9%. In the evening period (18:30–01:00), LoS A improved from 79.5% to 97.4

In the inbound direction, a similar improvement in LoS distribution is observed. In the morning peak, LoS A increased from 59.1% to 93.9%, with the remaining 6.1% under LoS B and no instances of LoS C to F. During midday, the share of LoS A rose from 44.2% to 89.0%, and LoS D to F, which initially accounted for 10.9%, were fully eliminated. The evening peak shows an increase in LoS A from 60.2% to 97.0%, and in the evening period, LoS A increased from 95.3% to 100.0%.

Table 6.6: Percentage distribution of LoS by period for Line 32 (Outbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	45.5	22.7	23.1	5.9	2.9	0.0	91.3	8.7	0.0	0.0	0.0	0.0
Midday (09:00–15:30)	35.9	30.0	23.9	6.9	2.2	1.0	89.8	9.2	1.0	0.0	0.0	0.0
Evening peak (15:30–18:30)	62.8	25.0	9.0	3.1	0.0	0.0	96.9	3.1	0.0	0.0	0.0	0.0
Evening (18:30–01:00)	79.5	14.1	3.8	2.6	0.0	0.0	97.4	2.6	0.0	0.0	0.0	0.0

Table 6.7: Percentage distribution of LoS by period for Line 32 (Inbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	59.1	19.3	15.5	4.4	1.7	0.0	93.9	6.1	0.0	0.0	0.0	0.0
Midday (09:00–15:30)	44.2	25.0	19.8	7.0	3.0	0.9	89.0	10.0	0.9	0.0	0.0	0.0
Evening peak (15:30–18:30)	60.2	22.1	14.7	3.0	0.0	0.0	97.0	3.0	0.0	0.0	0.0	0.0
Evening (18:30–01:00)	95.3	4.7	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0

6.7.2. Serviceline 33

In the outbound direction, the use of articulated buses resulted in an increase in the share of rides operating at LoS A. During the morning peak , the proportion of LoS A increased from 83.8% to 96.6%, while LoS B and C decreased from 9.4% and 3.4% to 3.0% and 0.4%, respectively. LoS D to F, which accounted for a combined 3.4% in the conventional scenario, were eliminated. During the midday period, LoS A increased from 69.6% to 96.2%, and LoS C to F were reduced from a combined 14.5% to 0.0%. The evening peak shows a similar pattern, with LoS A increasing from 65.2% to 93.9% and LoS D to F dropping from 6.1% to 0.0%. In the evening period, the share of LoS A rose from 74.8% to 100.0%.

In the inbound direction, the shift to articulated buses also led to an increase in LoS A across all time periods. During the morning peak, LoS A increased from 69.7% to 91.7%. LoS B and C decreased from 12.3% and 9.6% to 7.5% and 0.9%, respectively, and no LoS D to F occurred under the articulated scenario. During midday, LoS A increased from 74.4% to 95.3%, and LoS D to F, which collectively accounted for 4.7% under the conventional scenario, were reduced to 0.0%. In the evening peak, LoS A improved from 91.2% to 100.0%, and in the evening period, LoS A increased from 94.4% to 98.9%, with a minor share of LoS B remaining.

Table 6.8: Percentage distribution of LoS by period for Line 33 (Outbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	83.8	9.4	3.4	3.0	0.0	0.4	96.6	3.0	0.4	0.0	0.0	0.0
Midday (09:00–15:30)	69.6	15.9	10.7	3.0	0.8	0.0	96.2	3.8	0.0	0.0	0.0	0.0
Evening peak (15:30–18:30)	65.2	14.6	14.1	5.1	1.0	0.0	93.9	6.1	0.0	0.0	0.0	0.0
Evening (18:30–01:00)	74.8	17.9	7.3	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0

Table 6.9: Percentage distribution of LoS by period for Line 33 (Inbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	69.7	12.3	9.6	4.8	2.6	0.9	91.7	7.5	0.9	0.0	0.0	0.0
Midday (09:00–15:30)	74.4	14.3	6.6	3.2	1.1	0.4	95.3	4.3	0.4	0.0	0.0	0.0
Evening peak (15:30–18:30)	91.2	6.1	2.6	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0
Evening (18:30–01:00)	94.4	0.0	4.5	1.1	0.0	0.0	98.9	1.1	0.0	0.0	0.0	0.0

6.7.3. Serviceline 68

In the outbound direction, the introduction of articulated buses resulted in a notable increase in the proportion of LoS A across all time periods. During the morning peak, LoS A increased from 68.8% to 90.1%, while LoS D to F, which collectively represented 10.1% in the conventional scenario, were reduced to 0.0%. During the midday period, LoS A rose from 86.1% to 98.7%, and LoS C and D, initially accounting for 5.5%, were eliminated. In the evening peak, LoS A increased from 93.8% to 99.0%. In the evening period (18:30–01:00), LoS A remained at 100.0%

In the inbound direction, similar patterns were observed. During the morning peak, LoS A increased from 86.9% to 99.3%, and LoS C to F were eliminated. During midday, LoS A rose from 69.9% to 91.9%, while LoS D to F, which collectively represented 9.0%, were reduced to 0.0%. In the evening peak, the share of LoS A increased from 73.6% to 93.4%, with LoS D to F reduced from 6.5% to 2.2%. In the evening period, LoS A rose from 90.0% to 100.0%.

Table 6.10: Percentage distribution of LoS by period for Line 68 (Outbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	68.8	14.2	7.1	4.3	2.8	2.8	90.1	7.1	2.8	0.0	0.0	0.0
Midday (09:00–15:30)	86.1	8.4	4.2	1.3	0.0	0.0	98.7	1.3	0.0	0.0	0.0	0.0
Evening peak (15:30–18:30)	93.8	5.2	0.0	1.0	0.0	0.0	99.0	1.0	0.0	0.0	0.0	0.0
Evening (18:30–01:00)	100.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0

Table 6.11: Percentage distribution of LoS by period for Line 68 (Inbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	86.9	9.0	3.4	0.0	0.7	0.0	99.3	0.7	0.0	0.0	0.0	0.0
Midday (09:00–15:30)	69.9	14.1	7.9	3.2	2.6	2.4	91.9	5.8	2.4	0.0	0.0	0.0
Evening peak (15:30–18:30)	73.6	13.2	6.6	3.8	0.5	2.2	93.4	4.4	0.0	2.2	0.0	0.0
Evening (18:30–01:00)	90.0	10.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0

6.7.4. Serviceline 70

In the outbound direction, the deployment of articulated buses led to an increase in the share of LoS A across all time periods. During the morning peak, LoS A rose from 64.8% to 88.3%, and the combined share of LoS D to F, which was 11.6% under the conventional scenario, was reduced to 0.0%. During the midday period, LoS A increased from 62.2% to 91.8%, with LoS D to F decreasing from 8.2% to

0.4%. In the evening peak, LoS A rose from 78.0% to 95.9%, while LoS D to F decreased from 4.2% to 0.0%. In the evening period, LoS A increased from 97.6% to 100.0%.

In the inbound direction, similar improvements were observed. During the morning peak, the share of LoS A increased from 69.6% to 91.5%, and LoS D to F decreased from 8.5% to 1.0%. During the midday period, LoS A rose from 60.2% to 92.9%, with LoS D to F reduced from 7.0% to 0.0%. In the evening peak, LoS A increased from 84.7% to 95.0%, and LoS D to F dropped from 4.9% to 0.2%. During the evening period, LoS A increased from 93.7% to 99.6%.

Table 6.12: Percentage distribution of LoS by period for Line 70 (Outbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	64.8	15.3	8.2	5.5	3.4	2.7	88.3	8.9	2.7	0.0	0.0	0.0
Midday (09:00–15:30)	62.2	19.3	10.4	4.6	1.6	2.0	91.8	6.2	1.6	0.4	0.0	0.0
Evening peak (15:30–18:30)	78.0	13.3	4.6	3.0	0.5	0.7	95.9	3.4	0.7	0.0	0.0	0.0
Evening (18:30–01:00)	97.6	2.4	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	0.0

Table 6.13: Percentage distribution of LoS by period for Line 70 (Inbound)

Period	Conventional bus						Articulated bus					
	A	B	C	D	E	F	A	B	C	D	E	F
Morning peak (06:00–09:00)	69.6	15.1	6.8	4.8	1.2	2.5	91.5	6.0	1.4	0.6	0.4	0.0
Midday (09:00–15:30)	60.2	20.3	12.4	4.3	1.7	1.0	92.9	6.1	1.0	0.0	0.0	0.0
Evening peak (15:30–18:30)	84.7	7.1	3.2	2.7	1.1	1.1	95.0	3.9	0.9	0.2	0.0	0.0
Evening (18:30–01:00)	93.7	2.8	3.2	0.4	0.0	0.0	99.6	0.4	0.0	0.0	0.0	0.0

6.8. Conclusion of the data analysis

The aim of this chapter was to answer the following subquestion: *What is the current Level of Service on crowding and how could the use of articulated buses enhance this level?* By analysing AFC data of service line 32,33,68 & 70 from week 45, November 2023 this subquestion could be adressed.

All analysed service lines exhibited a LoS of level F. For lines 70 and 68, this crush load occurred more structurally. Line 70 experienced persistent crush loads in both directions, whereas line 68 showed a more asymmetric pattern, with high outbound occupancy during the morning peak and crowding in the inbound direction spread across the rest of the day. For both lines, the crush load is concentrated on relatively short segments of the route. For line 70, this may be explained by its popularity as a connector to transfer points, where many passengers alight or board. In the case of line 68, the segment leading to a high school likely accounts for the peak in demand, as occupancy levels drop significantly after the bus passes the school.

Lines 33 and 32 also showed occurrences of crush load, though less frequently. Line 33, which serves the airport, may experience overcrowding particularly when tourist flights arrive, as it is the sole line connecting the airport to the network. Line 32 did not display persistent crush load, but rather showed consistently high occupancy across the entire route, resulting in fewer intervals with acceptable quality levels.

Nevertheless, all routes indicate issues with crush load. It should also be noted that the analysis does not account for on-board conditions. For instance, school children carrying large bags may reduce available standing space, meaning the crush load could in reality be reached already at levels E or D rather than F.

When the analysis is conducted with the capacity modelled for an articulated bus instead of the conventional bus, significant improvements are observed. For all lines, Level F (the crush load) is no longer present. On line 70, only a very small portion of Level E is observed during the morning peak in the inbound direction, while for the other service lines, Level E is entirely eliminated. Level D is still observed in small portions on line 70 and, to a lesser extent, on line 68. In addition to the elimination of lower LoS levels, substantial improvements are noted in the higher levels (A, B, and C) for all the analysed service lines.

7 Ridership effects

This section presents the results of the simualtions with the OV-Lite model, which examine the impact on ridership when deploying articulated buses within the network. The analysis follows a two-step approach. The first step involves adjusting only the service frequency. By either increasing or reducing the frequency during a specific timeframe, the effect on ridership becomes visible when compared to the reference scenario, where no frequency changes occur.

The second step investigates the impact of replacing conventional buses with articulated ones. In this case, both the service frequency and the speed factor change. The speed factor reflects improvements in perceived travel time, driven by enhanced comfort and reduced crowding in articulated buses.

7.1. Service Frequency Effects

First, only the effects of frequency changes are assessed. Table 7.1, along with Figures 7.1, 7.2, and 7.3, presents the results of these simulations. The simulation approach is as follows: during the morning (06:00–09:00) and evening peaks (15:30–18:30), the service frequency is gradually reduced to two vehicles per hour, while during the midday period (09:00–15:30), the frequency is gradually increased to eight vehicles per hour. All the frequency adjustments are done in both directions. The ridership values in bold indicate the current ridership for each service line.

Table 7.1: Ridership per Frequency and Time Period (Speed Factor 1.0)

Freq.	**Morning Peak**				**Midday**				**Evening Peak**			
(bph)	**70**	**68**	**33**	**32**	**70**	**68**	**33**	**32**	**70**	**68**	**33**	**32**
8	**1769**	–	–	–	6267	2234	2721	3242	**1745**	–	–	–
7	1563	–	–	–	5643	2112	2603	2963	1521	–	–	–
6	1333	**557**	–	**592**	**4881**	**1954**	2451	2670	1281	**532**	–	**754**
5	1021	491	–	488	–	–	2244	2302	999	473	–	605
4	692	410	**582**	365	–	–	**1951**	**1857**	690	395	**420**	433
3	360	302	443	196	–	–	–	–	366	286	313	202
2	134	156	252	58	–	–	–	–	135	142	165	46

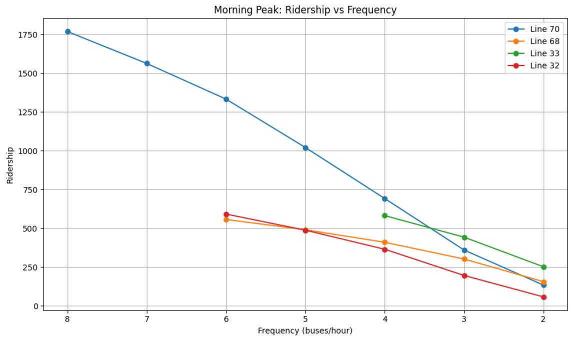


Figure 7.1: Ridership impact during the morning peak

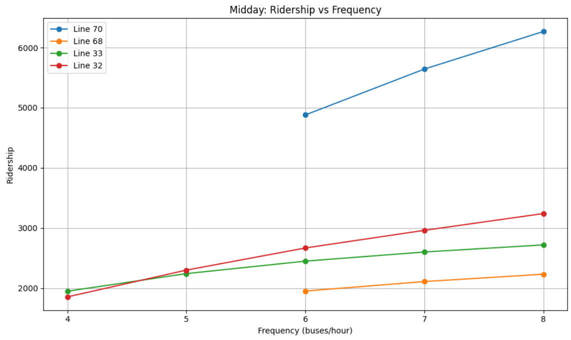


Figure 7.2: Ridership impact during the midday off-peak

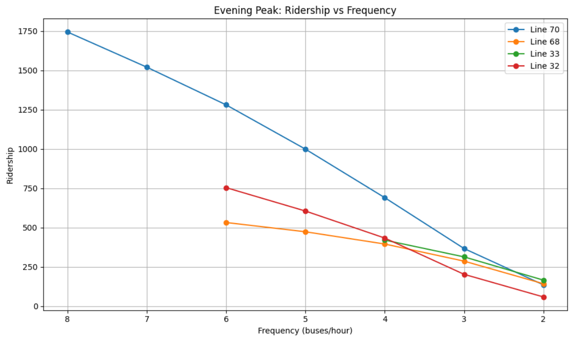


Figure 7.3: Ridership impact during the evening peak

During the morning peak, the results show a clear negative correlation between service frequency and ridership for the service lines. Line 70, for example, exhibits an average decrease of 15.4% in ridership per step reduction in frequency, while Line 68 shows a comparable decline of 18.0%. Line 33 also demonstrates a significant reduction, with a mean decline of 28.3% per step and last but not least service line 32 shows a reduction of 15.1% per 1 less vehicle per hour.

By contrast, the midday results indicate a positive response to increases in service frequency, reflecting the effect of additional vehicles per hour. Line 70 shows an average ridership increase of 14.2% per added vehicle, followed by Line 68 with a 7.2% gain. Line 33 reports an average increase of 9.8%, while Line 32 exhibits the highest elasticity, with ridership rising by 18.6% for each additional bus per hour.

During the evening peak, ridership again demonstrates considerable sensitivity to changes in service frequency. Line 70 experiences an average decrease of 11.5% in passenger numbers for each vehicle removed per hour, while Line 68 shows a steeper decline of 18.3%. Line 33 is the most affected, with a ridership reduction of 30.3% per step. Line 32 also shows significant sensitivity, with an average decrease of 23.5% for each one-vehicle-per-hour reduction.

7.2. Ridership Effects with Articulated Bus Deployment

In the second set of simulations, the effect of improved QoS due to the increased comfort, capacity and reliability of the articulated bus was analysed. Via the speedfactor included in the OV-Lite model the perceived travel time could be improved. In the OV Lite model, this was captured through speed factors of 1.1, 1.2 and 1.3, representing a 10%, 20%, or 30% reduction in perceived travel time. These scenarios allowed an assessment of how enhanced quality of service affects ridership, both under high-frequency and low-frequency service levels.

Whereas the earlier analysis of frequency reduction extended down to two vehicles per hour, the current analysis is limited to a minimum of four vehicles per hour. This adjustment reflects a more realistic operational scenario and ensures that the LoS related to frequency remains within the higher quality range.

7.2.1. Morning Peak

Tables 7.2 to 7.4 present the ridership results for the service lines during the morning peak, with an applied speed factor ranging from 1.1 to 1.3 (representing a 10% to 30% improvement in perceived travel time). The values in brackets next to each service line indicate the ridership levels in the reference scenario.

Table 7.2: Ridership per frequency (Morning Peak), speed factor 1.1

Frequency (bph)	**Line 70** (1769)	**Line 68** (557)	**Line 33** (582)	**Line 32** (592)
8	1938	–	–	–
7	1734	–	–	–
6	1469	606	–	653
5	1168	536	–	544
4	833	453	614	404

Table 7.3: Ridership per frequency (Morning Peak), speed factor 1.2

Frequency (bph)	**Line 70** (1769)	**Line 68** (557)	**Line 33** (582)	**Line 32** (592)
8	2093	–	–	–
7	1876	–	–	–
6	1627	649	–	707
5	1296	577	–	595
4	938	491	638	448

Table 7.4: Ridership per frequency (Morning Peak), speed factor 1.3

Frequency (bph)	**Line 70** (1769)	**Line 68** (557)	**Line 33** (582)	**Line 32** (592)
8	2242	–	–	–
7	2017	–	–	–
6	1751	684	–	759
5	1416	611	–	642
4	1035	522	661	489

The results indicate that improvements in perceived travel time can have a considerable impact on ridership. For example, during the morning peak, bus line 70 operates under baseline conditions at a maximum frequency of 8 buses per hour, carrying 1,769 passengers. When the speed factor increases to 1.1, ridership rises to 1,938 passengers; with a factor of 1.2, it increases further to 2,093; and at 1.3, the number of passengers reaches 2,242.

Conversely, a reduction in service frequency has a notable adverse effect on ridership. For the same line 70, it can be observed that a 10% improvement in perceived travel time nearly restores baseline ridership, while a 20% improvement results in a modest increase. However, this compensatory effect is only sufficient when the frequency is reduced by a single bus per hour. When the frequency is reduced to 6 buses per hour, even improvements of up to 30% in perceived travel time are insufficient to fully recover the original ridership levels, however the difference is not that big.

A similar pattern can be observed for lines 68 and 32 during the morning peak. A 10% improvement in perceived travel time mitigates the ridership loss caused by reduced frequency, while a 20% improvement fully restores the baseline levels. However, as with line 70, reducing the frequency by more than one vehicle per hour results in ridership levels that cannot be recovered, even with a 30% improvement in perceived travel time.

Line 33 operates at a frequency of 4 vehicles per hour during the morning peak. As reducing the frequency below this level would negatively affect the quality of service, further reductions are not considered. Instead, the deployment of articulated buses on this line yields moderate ridership increases: from 582 passengers under baseline conditions to 617 with a 10% improvement in perceived travel time, 638 with a 20% improvement and 661 with a 30% improvement.

7.2.2. Midday

Tables 7.5 to 7.7 present the ridership results for the service lines during the midday. Again, the values in brackets next to each service line indicate the ridership levels in the reference scenario.

Table 7.5: Ridership per frequency (Midday), speed factor 1.1

Frequency (bph)	**Line 70** (4881)	**Line 68** (1954)	**Line 33** (1951)	**Line 32** (1857)
4	–	–	2053	2031
5	–	–	2351	2500
6	5371	2051	2556	2891
7	6158	2213	2710	3204
8	6874	2345	2870	3485

Table 7.6: Ridership per frequency (Midday), speed factor 1.2

Frequency (bph)	**Line 70** (4881)	**Line 68** (1954)	**Line 33** (1951)	**Line 32** (1857)
4	–	–	2134	2185
5	–	–	2433	2686
6	5843	2136	2638	3082
7	6683	2309	2792	3416
8	7380	2437	2910	3748

Table 7.7: Ridership per frequency (Midday), speed factor 1.3

Frequency (bph)	**Line 70** (4881)	**Line 68** (1954)	**Line 33** (1951)	**Line 32** (1857)
4	–	–	2202	2327
5	–	–	2500	2848
6	6269	2210	2707	3254
7	7141	2387	2860	3627
8	7872	2518	2979	3973

During midday, the off-peak period, frequency could be increased while deploying articulated buses. For all the service lines it applies that with additional service frequency, significant ridership increases can be achieved.

Line 70 exhibits the highest sensitivity to frequency enhancements, with an average increase of 693 passengers per additional bus per hour (bph) between 6 and 8 bph. Line 32 also shows a strong positive response, with an average increase of 346 passengers per bph over the 4 to 8 bph range. In comparison, Line 33 demonstrates a more moderate growth, averaging 193 passengers per frequency increment. Line 68, by contrast, shows the smallest increase, with an average of 140 passengers per added bph. These findings suggest that Lines 70 and 32 experience the most substantial midday demand elasticity with respect to frequency.

When accounting for improved passenger experience through reduced crowding, simulated by applying speed factors that shorten perceived travel time, further ridership gains are observed. As the speed factor increases from 1.0 to 1.3, the marginal ridership response per additional bph grows consistently for all lines. For Line 70, the average gain per added bph rises to 754 with a 10 percent speed improvement, to 759 with a 20 percent improvement and to 801 with a 30 percent improvement. A similar pattern is observed on Line 32, where average increases reach 429, 441 and 461 respectively. The more modest responses of Line 33 and Line 68 also show slight improvements, indicating that while these lines remain less elastic, their attractiveness still benefits from perceived reductions in travel time.

7.2.3. Evening Peak

As last tables 7.8 to 7.10 present the ridership results for the service lines during the evening peak. Again, the values in brackets next to each service line indicate the ridership levels in the reference scenario.

Table 7.8: Ridership per frequency (Evening Peak, speed factor 1.1)

Frequency (bph)	**Line 70** (1745)	**Line 68** (532)	**Line 33** (420)	**Line 32** (754)
8	1938	–	–	–
7	1712	–	–	–
6	1446	570	–	842
5	1149	509	–	690
4	826	428	450	487

Table 7.9: Ridership per frequency (Evening Peak, speed factor 1.2)

Frequency (bph)	**Line 70** (1745)	**Line 68** (532)	**Line 33** (420)	**Line 32** (754)
8	2128	–	–	–
7	1881	–	–	–
6	1622	604	–	930
5	1293	537	–	761
4	950	453	471	546

Table 7.10: Ridership per frequency (Evening Peak, speed factor 1.3)

Frequency (bph)	**Line 70** (1745)	**Line 68** (532)	**Line 33** (420)	**Line 32** (754)
8	2297	–	–	–
7	2072	–	–	–
6	1765	632	–	1009
5	1431	565	–	831
4	1059	475	486	600

The results of the evening peak analysis show patterns similar to those observed during the morning peak. For Line 70, baseline ridership is 1,745 passengers. A reduction in frequency by one vehicle per hour leads to a decline in ridership, which can be compensated for by a 20% improvement in perceived travel time. Notably, in this case, a frequency reduction of two vehicles per hour (to 6 bph) can also be offset if the perceived travel time is improved by 30%.

For Line 68, the baseline ridership is 557 passengers. A reduction of one bus per hour can be nearly compensated by perceived travel time improvements of 10% or 20%, but not fully. A 30% improvement, however, restores ridership to baseline levels. A reduction of two buses per hour cannot be fully offset under any of the tested improvement scenarios.

For Line 33, the situation mirrors that of the morning peak. This line already operates at a frequency of four buses per hour and any further reduction would significantly degrade service quality. Therefore, deploying articulated buses presents a viable strategy, with ridership increasing to 450, 471 and 486 under perceived travel time improvements of 10%, 20% and 30% respectively, compared to the baseline of 433.

In the case of Line 32, the baseline evening peak ridership is 754 passengers. A frequency reduction to five buses per hour can be fully compensated by a 20% improvement in perceived travel time. However, when reduced to four buses per hour, none of the tested improvement scenarios are sufficient to restore baseline ridership levels.

7.3. Conclusion of the Simulations

The aim of this chapter was answering the following subquestion *What is the expected impact on ridership when articulated buses are introduced into the network?*

This subquestion was answered by running simulations using the OV-Lite model running on Omni-TRANS software. Various scenario's were determined starting with solely frequency changes. Here it was determined that lowering the service frequency can significantly lower ridership. Especially for a crowded popular service line like 70 up to more than 15% of the passenger can be lost due per one less vehicle per hour good for around 200 passengers.

Then later, the simulation were performed again but with different speedfactors which can lower the perceived travel time. This included perceived travel time reductions with 10%, 20% and 30%. With the speed factors applied, ridership can gradually recover from losses due to lower service frequency. Generally speaking if the service frequency is lowered by one, the ridership amount of the baseline scenario can be recovered if the comfort effects allow for around 20% reduction in perceived travel time. 10% partly mitigates the lost ridership and 30% even can cause more passengers to use the bus compared to the baseline results. The restore effects are howevere limited to lowering by one vehicle per hour. If service frequency is lowered by two buses per hour the comfort effects can mitigate the impact however no full restore is seen (except for one scenario: busline 70, eveningpeak, 30% perceived travel time reduction)

The midday simulations show postive results towards ridership. With no improvements in perceived travel time more buses per hour can substantially increase ridership. Especially service lines 70 and 32 can attract more passengers. Here line 70 on average increases ridership by 14.2% and line 32 18.6% good for around 700 and 350 passengers extra respectively. The somewhat less popular lines (33 & 68) also get extra passengers but with a relative small amount extra.

When the perceived travel time is improved during midday, these numbers increase even further. An increase in the speed factor from 1.0 to 1.1 to 1.3 leads to a rise in ridership of approximately 5% to 20%, depending on the service frequency and bus line. Although these results indicate a positive effect on ridership, it remains uncertain to what extent perceived travel time can realistically be improved, as the overall QoS is only slightly enhanced—mainly due to reduced crowding.

8
Conclusion & Discussion

The objective of this thesis was to answer the main research question: *What are the impacts of the deployment of articulated buses?*

It was found that crowding significantly influences both the passenger experience and operational performance. Crowding affects nearly all elements that together constitute the overall QoS. The constructed CLD illustrates that crowding can result in reduced reliability, increased perceived travel time, denied boardings, and diminished comfort. In addition, a negative reinforcing feedback loop may occur due to bus bunching, leading to further declines in punctuality. This in turn exacerbates reliability issues and reduces operational efficiency, as the first bus in a bunch may be overcrowded while subsequent buses remain underutilised.

Beyond these adverse effects on passengers, crowding also impacts bus drivers. Lower reliability, frequent denied boardings, and dissatisfied passengers can increase tension on board, leading to deteriorating working conditions. This may result in higher levels of absenteeism or even staff attrition. In turn, reduced driver availability can limit service levels and further aggravate crowding, thereby reinforcing the problem.

Zooming into the case of the RET, AFC data analysis showed that deploying articulated buses can substantially improve the LoS associated with crowding. On existing routes, LoS levels D, E, and F were observed frequently. When assuming buses with 60 instead of 35 seats, all occurrences of Level F disappeared, and most cases of Level E and D were reduced. Consequently, higher LoS levels such as A, B, and C became significantly more common. These results indicate a clear improvement in crowding conditions and could ultimately enhance the overall QoS.

The data-analysis is based on the assumption that deploying articulated buses does not require changes to service frequency or ridership. In practice, however, such deployments often coincide with frequency adjustments. To explore the effects this has on ridership, simulations were conducted using the OV-Lite model. The results indicated that a reduction in service frequency negatively affects ridership. However, this loss can be mitigated if passengers perceive a sufficient improvement in travel experience as a result of the articulated bus. Specifically, a 20 percent improvement in perceived travel time (used as a proxy for increased comfort) was generally sufficient to compensate for a reduction of one vehicle per hour. Reductions of more than two vehicles per hour could not be fully offset by comfort gains, although the negative impact was somewhat softened.

Given that concession agreements often require a minimum number of service kilometres to be operated, the effect of increasing frequency during off-peak hours was also examined. This measure aimed to compensate for the reduced amount of service kilometres during peak periods. The results indicated potential ridership growth with increased capacity, especially on routes in densely populated areas, particularly line 32, which serves the city centre, and line 70, which runs through dense neighbourhoods and is connected to major transfer points.

If a PT operator decides to deploy articulated buses within the network, several operational and infrastructural considerations must be taken into account. From an infrastructure perspective, the introduction of longer vehicles may require physical modifications such as larger bus bays and adjustments to maintenance depots. Although peer operators reported minimal issues with manoeuvrability due to favourable turning radii, this largely depends on the specific vehicle type and network characteristics. As such, route-level evaluations may be necessary to determine whether certain adjustments or restrictions apply.

Another important consideration concerns the choice of propulsion technology. A diesel-powered articulated bus would typically be able to operate throughout the entire day without refuelling. In contrast, a battery-electric articulated bus has a more limited range and requires recharging. This may necessitate the installation of charging infrastructure at terminals or intermediate stops, or alternatively, charging at the depot. In the latter case, additional vehicles may be needed to cover peak demand due to increased downtime, and more deadheading kilometres may be incurred. Overall, this could also require bus drivers to 'slip', leading to more complex duty schedules. An overview of all considerations accompanied by the deployment of articulated buses can be found in Figure 5.3.

Overall the deployment of articulated buses can contribute to improved QoS by reducing crowding and enhancing the overall passenger experience. Although infrastructural and operational adjustements could be required, particularly in the case of buses powered by electricity, peer operators have reported a relatively smooth transition, often resulting in service improvements that better align with passenger demand. The increased capacity of articulated buses may also allow operators to reduce service frequency without a significant loss of passengers. Any potential loss in ridership due to a lower frequency may be mitigated, fully recovered, or even exceeded, depending on the extent to which perceived travel time is improved through reduced crowding.

8.1. Discussion

This thesis has several limitations. First, while the constructed CLD clarifies relationships between key variables, it does not provide insight into the magnitude of these effects. As a result, it remains unclear to what extent crowding impacts the exploitation, making it difficult to prioritise interventions effectively.

For the data-analysis a correction factor was applied to account for OVPay usage and fare evasion, but the accuracy of this factor remains uncertain. Applying it uniformly across all stops and time periods may lead to misrepresentations, as payment behaviour and boarding patterns likely vary depending on the context. A more differentiated, context-sensitive correction method would likely yield more accurate results. In addition, the AFC dataset does not capture denied boardings. Since only successful check-ins are recorded, passengers who are unable to board due to overcrowded conditions remain invisible in the data, even though they represent a critical component of capacity shortfall. Furthermore, the assumption that Level F always corresponds to crush capacity is overly simplistic, as crowding is highly context dependent. For example, a bus full of schoolchildren carrying large backpacks may already exceed practical capacity at Level of Service D or E, as the backpacks occupy considerable space and reduce the actual usable area, even when the formal passenger load remains within standard thresholds.

As also emphasised by Li and Hensher (2013b), crowding is not solely determined by objective passenger load, but is also strongly shaped by subjective perception. That is, crowding reflects not only how many people are on board, but also how passengers experience space, comfort, and movement within the vehicle. Moreover, the dataset covers only one week and lacks contextual operational information, making it unclear whether the observed conditions reflect typical service patterns or are influenced by temporary disruptions, such as roadworks or diversions. Seasonal variation in travel demand is likewise not captured, which limits the generalisability of the findings.

For the simulation part it should be noted that the model assumes immediate passenger awareness of service improvements, without accounting for the time required for behavioural adaptation. Moreover, the effects of deploying articulated buses on ridership across other lines and on the total volume of passenger-kilometres remain undetermined. The model also fails to differentiate between captive and non-captive passengers, potentially neglecting important behavioural distinctions. Lastly, although increased comfort is assumed to reduce perceived travel time and thereby attract new passengers, it remains unclear at what threshold this perceived improvement leads to excessive demand, ultimately resulting in renewed crowding. This dynamic is also reflected in the CLD, which illustrates that the relationship between QoS and ridership constitutes a balancing loop that eventually stabilises at an equilibrium.

It is also important to highlight the broader context in which this research was conducted. The study originated in response to growing capacity issues on certain RET bus lines, in combination with a persistent shortage of bus drivers, which currently hinders the ability to increase service frequency. Within this setting, deploying articulated buses appeared to be a promising solution to alleviate crowding without requiring additional staff.

However, articulated buses should not be viewed as a universal or standalone solution. This thesis focused on a single intervention in detail, but did not include a comparative analysis of alternative measures. Although such an in-depth approach yields useful insights, it does not indicate whether this is the most suitable intervention in a broader strategic context.

Consider, for example, RET line 33, which connects Rotterdam The Hague Airport to the central station. During holiday periods, this line becomes heavily utilised by travellers with large luggage, leading to substantial crowding. While deploying articulated buses could address this issue, an alternative solution might involve targeted communication strategies that encourage passengers to transfer to the metro at Meijersplein, as originally intended. In such a case, the introduction of larger buses could represent an excessive and costly intervention.

9 Recommendations

This chapter outlines several recommendations to strengthen the reliability and practical applicability of the current research. These recommendations address methodological improvements, data integration, and simulating refinements that could support better-informed decision-making regarding the deployment of articulated buses.

9.1. Enhancing the CLD

The CLD as it is constructed now illustrates the relationships between the key variables and factors influencing the QoS, ridership and operational performance. However, the model does not yet account for the relative strength or quantitative magnitude of these relationships. To increase its analytical value, it is recommended to expand the CLD by incorporating numerical weights or elasticity values based on empirical data or expert estimates. Doing so would allow the CLD to better reflect system dynamics and enable stakeholders to prioritise intervention points based on their relative impact.

9.2. Developing the Considerations Framework

The current considerations framework gives a insight in the decision-making process and a holistic overview of the consideration accomponied by these decisions. However, it is not yet clear what the hight of certain investment costs are and if these costs can be earned back later and how it would influence the operational costs. It is therefore advised to expand the framework by integrating cost estimates for each consideration. These could include capital investment for vehicle procurement, depot modifications, and infrastructure adjustments, as well as operational cost implications such as maintenance and driver deployment. A quantified framework would enable cost-benefit comparisons and facilitate transparent trade-off discussions among stakeholders. A drawback is that what the outcomes of these costs are is very dependend on which type of bus the operator is considering and the lay-out of the network. For example an operator with already enough space in its maintenance depot or already lare enough bus bays would have to make substantially lower adjustments then an operator which have to adjust almost everything. A quantified framework would enable cost-benefit comparisons and facilitate transparent trade-off discussions among stakeholders.

9.3. Improving the Data Analysis Approach

The data analysis primarily relies on smart card transaction data, which provides valuable insights into boarding and alighting behaviour. However, several methodological enhancements are recommended to improve the analysis:

- **Automated Passenger Counters (APCs):** Currently, our analysis relies on AFC data. While this provides valuable insights into bus occupancy rates, it doesn't account for passengers using OV-Pay (a contactless payment system) or those who evade fares. Implementing APCs would resolve this issue by accurately measuring the actual number of occupants on the bus, offering a more precise reflection of ridership.

- **Inclusion of Denied Boardings:** The analysis as it is now does not incoperate denied boardings. Denied boardings play an important role in assessing the QoS of a service line. Also by incoperating the denied boardings better insight is given on how it would influence the crowding LoS as it now can tell how full the bus actually is because now the denied boarding passengers can step in due to the higher capacity of the articulated bus.
- **Combining Quantitative and Perceptual Measures:** Crowding is not solely a function of load factors; perceived crowding also plays a crucial role in passenger satisfaction. It is therefore recommended to complement quantitative occupancy data with survey-based insights to capture subjective passenger experiences more holistically.

9.4. Improving the Ridership Simulations

The current ridership simulations provide indicative insights into potential changes in demand following the deployment of articulated buses. However, several refinements are necessary to strengthen the model's realism and predictive power:

- **Synchronisation of the origin-destination data:** The current data analysis and model outcomes show discrepancies in ridership values and the identification of crowded segments. Segments often labeled as crowded in the data analysis are not consistently identified as such in the OV-Lite model. Synchronising the origin-destination data for the OV-Lite model would lead to more reliable results. This improvement would expand the model's application beyond mere shadow analysis, allowing for broader and more dependable use.
- **Validation Against Real-World Outcomes:** Currently, the analysis provides insights into potential outcomes rather than validated results. It would be valuable to validate these findings against real-world data once the deployment of articulated buses proceeds, in order to understand the actual effect of articulated buses on ridership.
- **Longitudinal Effects:**The model currently assumes passengers immediately adapt to new service patterns and articulated buses, which is not realistic. In reality, such adaptation takes time. Research into the dynamic passenger response or the adaptation period for ridership to reach equilibrium would provide valuable insight into the time-dependent evolution of ridership and the true impact of service changes. This would help to understand how ridership changes over time until it approaches a stable state, offering a more nuanced and accurate understanding of passenger behavior.
- **Network-Wide Implications:** The deployment of articulated buses on a single line could have broader implications for travel behaviour across the entire network. For instance, it would be important to assess what the deployment of articulated buses might mean for ridership on nearby tram lines. Additionally, understanding the ultimate effect on total passenger-kilometres across the network is crucial. Gaining insight into these numbers would provide a more comprehensive view for informed decision-making regarding public transport strategies.
- **Iterative Passenger Assignment** Inspired by the OV-Lite model used by HTM, it is recommended to implement an iterative passenger assignment mechanism based on the passenger load within the bus. This enhancement would not only enable passengers in the model to dynamically assign themselves to routes and modes, but also facilitate the adjustment of the speed factor (or crowding factor) based on the real-time passenger occupancy.

  Passengers inherently perceive crowding differently depending on whether they are seated or standing. The current model, however, treats all occupancy equally, regardless of whether passengers are seated or standing. Standing crowding is generally perceived as more discomforting, as emphasized by research such as that by (Zuo et al., 2019). Incorporating this distinction—by differentiating the perceived disutility of standing versus seated passengers—could significantly improve assessments of perceived service quality and lead to a more realistic and nuanced understanding of passenger experience.

9.5. Recommendations for the RET

Based on the analysis, it is recommended that RET prioritise the deployment of articulated buses. The data analysis revealed significant overcrowding on several lines, while the ongoing shortage of bus drivers makes increasing service frequency an unviable solution.

Line 70 emerges as the most problematic, both from the quantitative data and stakeholder interviews. It consistently reaches level F during nearly all time periods in both directions. It is therefore advised to deploy articulated buses on this line as a first step.

A logical next candidate is Line 68, which also frequently experiences overcrowding, likely due to high demand from secondary school pupils. However, the directional demand imbalance should be taken into account, as high demand in one direction results in overcapacity in the other.

Line 32 also shows signs of crowding, although to a lesser extent. As it serves the city centre and attracts passengers across its entire length, the buses are consistently well-occupied. Considering ongoing efforts to promote car-free urban areas and the resulting potential for ridership growth, the future deployment of articulated buses on this line is advisable.

For Line 33, no significant crowding issues were observed. Therefore, the deployment of articulated buses on this line is not recommended.

In addition, it is recommended that RET engage in discussions with the concession authority regarding the current obligation to operate a fixed number of service kilometres. This requirement constrains the operator's ability to respond flexibly to staff shortages and evolving travel demand. Should this obligation remain in place, increasing the frequency during the midday period on Lines 32 and 70 is recommended. These lines serve densely populated residential areas, city centres, and major transfer nodes, and maintain high ridership throughout the day.

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AI Statement

This thesis was written with the assistance of AI tools, primarily OpenAI's ChatGPT. These tools were used to support the writing process by helping to formulate and refine sentences, translate specific terms, and check grammar. The content, structure, and analysis presented in this thesis are entirely the result of the author's academic work, and all AI-generated content was critically reviewed and edited by the author.

A
Interviews within the RET

A.1. Bus operators

The first interview was conducted with E. van Houwelingen, the issue coordinator for bus drivers at the RET. In his role, he gathers and communicates the complaints of bus drivers to the RET's office. Van Houwelingen is also a bus driver himself, which gives him firsthand experience and insight into the challenges faced by his colleagues.

Van Houwelingen has observed that on certain bus service lines, the passenger demand exceeds the capacity of the traditional 12-meter buses. This issue presents challenges for passengers, bus operators, and the RET. For passengers, it means they are not receiving the service they expect from the RET. For the RET, the result is lost revenue as passengers choose alternative travel modes due to overcrowded buses. For bus drivers, the situation is further complicated by an increase in aggressive passenger behavior, likely stemming from the discomfort caused by overcrowding.

Van Houwelingen noted that the most significant issues occur on service lines that cater to school children, where demand can be particularly high.

He believes that transitioning to 18-meter buses could help address this problem by offering more capacity while maintaining the same number of bus drivers. This solution would alleviate overcrowding and, in turn, improve the experience for passengers, operators, and the RET.

A.2. S&O

The Strategic and Development (S&D) department of RET has highlighted that the current bus network is experiencing capacity challenges due to a shortage of bus drivers. However, the S&D department holds a different perspective, arguing that these capacity issues are concentrated on only a few specific routes and occur primarily at certain times, often in a single direction.

S&D suggests that reducing service frequency during morning peak hours while deploying articulated buses could help manage capacity constraints. While this approach may lead to a reduction in non-captive passengers during peak hours, it is expected to attract more passengers during non-peak periods due to an overall improvement in service quality.

Although S&D acknowledges that articulated buses could address the current capacity issues, they remain cautious about potential drawbacks. A key concern is the impact on network efficiency, as articulated buses would be limited to specific high-demand corridors. This restriction could reduce operational flexibility in deploying buses across the network, potentially lowering overall efficiency. As a result, S&D believes that this solution would be more suitable for a network exclusively serving high-demand corridors.

A.3. Maintenance manager

I spoke with the asset manager, who acknowledged that the bus network is facing capacity issues due to a shortage of drivers. He also pointed out that overcrowded buses are leading non-captive travelers to consider alternative modes of transport, as the perceived service quality is declining. According to him, the main factors affecting service quality are low comfort levels and poor reliability, including instances of denied boarding and inadequate on-time performance.

The asset manager considers articulated buses a viable solution for both the short and long term. However, he raises concerns about the robustness of this approach. Operating with 12-meter buses at a higher frequency provides greater resilience—if a bus is canceled, the next one arrives shortly after, ensuring that stranded passengers are accommodated. In contrast, while articulated buses can carry more passengers, a canceled trip could cause severe crowding issues, making service disruptions more problematic.

A.4. Asset Manager

The asset manager, in agreement with the other stakeholders, acknowledged that certain bus lines are experiencing capacity issues. Furthermore, he noted that overcrowding also contributes to fare evasion as effective surveillance becomes challenging under such conditions. The prevalence of successful fare dodging can then encourage others to evade fares as well, resulting in a contagious phenomenon. This behaviour is also described by Haghani and Nassir (2025), who emphasise that fare evasion is not solely a financial issue; social and psychological factors also play a significant role. When passengers perceive the public transport system as unfair—due to unreliable services, high fares, or insufficient investment—the tendency to evade fares increases. This observation suggests that, while price sensitivity influences fare evasion, perceptions of fairness and service quality are equally critical factors.

B

Interview with peer operators

B.0.1. HTM - The Hague

HTM indicated that, during their transition to articulated buses, several challenges emerged regarding the relocation of bus stops. These were related to municipal procedures, the involvement of the MRDH (the concession authority), and concurrent road reclassification efforts aimed at reducing speed limits from 50 km/h to 30 km/h. This reduction has led to longer emergency service response times, which are bound by legal requirements. As a result, emergency services have raised concerns about buses stopping directly on the carriageway, as stationary buses may further impede emergency access. Consequently, they have requested that buses on high-frequency routes (operating every 10 minutes or more) use designated bus bays. At HTM, all such high-frequency routes will be operated with articulated buses.

HTM also noted that the challenge of relocating bus stops was not solely caused by the introduction of articulated buses. The reduction in speed limits had already necessitated adjustments to stop locations. However, the adoption of articulated buses further complicated this process due to their greater length, which requires more space and different design considerations. HTM, however, benefited from the fact that over a decade ago it had already operated articulated buses, meaning that some stops were still suitable for this type of vehicle. At locations where rebuilding the stops would have taken too long, a temporary workaround was used. In these cases, parking spaces were repurposed to allow articulated buses to stop, but this was largely seen as a tolerated interim solution rather than a structurally sound or permanent one.

HTM chose to equip their articulated buses with three doors, consisting of one for boarding and two for alighting. This decision was based on two main considerations. First, adding a fourth door would often result in it aligning with physical obstacles such as trees, which would then need to be removed. This would further complicate the already challenging process of relocating bus stops, as the removal of existing physical elements like trees often leads to policy and procedural difficulties. By limiting the number of doors to three, such issues can be avoided. Second, simulation results conducted by HTM indicated that an additional door would not significantly reduce dwell time, and that three doors are sufficient to ensure efficient passenger flow. The same door configuration has also been adopted for their new fleet of conventional twelve-metre buses.

From an infrastructure perspective, HTM conducted test rides to assess whether the articulated buses could operate on the required routes. These tests revealed no issues, and the articulated buses were able to navigate all routes where their deployment was planned. According to HTM, this is largely due to the turning radius of an articulated bus being very similar to that of a conventional twelve-metre bus. This similarity is attributed to the shorter wheelbase of the front section. Depending on the specific design of the articulated bus, the rear section tends to follow the front section closely, ensuring that turning does not present significant difficulties. In addition, HTM's articulated buses are even slightly narrower than conventional buses, as the side mirrors have been replaced with camera systems.

HTM indicated that they borrowed an articulated bus from EBS, another operator active in The Hague and its surroundings. Together with municipal staff, they conducted test rides along the planned routes to identify any potential infrastructural or operational issues. These test rides provided valuable insights regarding infrastructure and bus stops, which were then used to inform decisions regarding the adoption and deployment of articulated buses.

A key tradeoff for HTM was operational flexibility. Introducing a mixed fleet would reduce this flexibility, as articulated buses must remain assigned to specific routes due to their size and infrastructure requirements. For HTM, the choice was between purchasing a limited number of articulated buses for select trips or fully transitioning to articulated buses on certain lines. They opted for a complete transition on the lines where there had been uncertainty, particularly those experiencing consistent crowding throughout the broader peak periods, not just during isolated rush hour trips. Additionally, off-peak demand played a role, largely due to high numbers of secondary school students using the service, many of whom travel before the main commuter peak begins. Previously, HTM had to plan additional reinforcement services to accommodate these passengers. With the introduction of articulated buses operating throughout the day, this extra capacity is now structurally embedded. While overall fleet flexibility has decreased, this is compensated by the fact that the fleet is well balanced, with even slightly more articulated buses than conventional ones.

Another important change, which is also related to the shift to electric buses, concerns the way drivers operate during the day. Traditionally, a driver would remain with the same bus throughout their entire shift. However, this is no longer possible. The bus now remains assigned to a specific service line for the entire day, while the driver changes buses during their shift. This practice, referred to as ”slippen”, enables more efficient deployment of the bus fleet. It allows for better optimisation of vehicle use, taking into account battery capacity, charging requirements, and the need to guarantee sufficient range throughout the operating day.

One reason why HTM delayed the transition to articulated buses was their decision to wait for further developments in battery technology. According to HTM, this proved to be a wise choice, as modern batteries now offer significantly improved range, making the operation of electric articulated buses much more feasible.

Another important tradeoff for HTM concerned the placement of charging facilities. As articulated buses are longer, they consume more energy and cannot operate a full day without recharging. To address this, HTM decided to install charging infrastructure at the start and end points of selected service lines. This allows buses to recharge during layovers when needed, so that, once sufficiently charged, they can resume service with a new driver. However, not all lines are equipped with such facilities. For example, Line 25, operated by HTM, lacks charging infrastructure at its termini. As a result, buses on this line must return to the maintenance facility for charging. To accommodate this additional operational movement and maintain service levels, HTM was required to procure additional articulated buses.

Regarding the transition for operators, HTM indicated that the change has felt significant for many staff members working in operations. Drivers, in particular, have had to adjust to the need for regular charging, which was not previously part of their routine. In addition, the practice of ”slippen”, where drivers change buses during their shift, is not widely appreciated. Drivers typically personalise their driving environment at the start of their shift, and having to switch vehicles repeatedly requires them to reset everything each time.

HTM also noted that some drivers, especially younger ones, find it exciting but also slightly intimidating to drive an articulated bus. However, an additional driving licence is not required. For those who are apprehensive, HTM offers additional instruction to help them become comfortable with the new vehicle. According to drivers who have already made the transition, the articulated bus handles very well. Although the first ride may feel daunting, they reported becoming accustomed to it quickly.

Operational managers have also expressed some nervousness about the transition, particularly due to concerns about a potential increase in vehicle damage. However, HTM believes this should not be attributed to the length of the bus, but rather to the fact that it is a new type of vehicle. HTM emphasised that significant effort has been made to involve all staff in the transition process to ensure that everyone can adapt and feel confident with the change.

HTM operates under service regulations set by the MRDH, one of which requires that a minimum number of service kilometres be delivered annually. Due to the use of articulated buses, which offer higher capacity, HTM was able to reduce service frequency during peak hours. However, this reduction meant that the required number of service kilometres was no longer met. To address this, HTM increased service frequency during off-peak hours.

According to HTM, peak-hour frequency remains high enough that passengers can still reach a stop without needing to check the timetable, maintaining a good level of service. Moreover, passenger feedback revealed that there was also demand for higher service frequency during off-peak periods, including evenings. For instance, some lines continued to operate at maximum capacity in the evenings, as previous frequencies were too low to meet demand. By reallocating some of the service frequency from peak to off-peak periods, HTM not only met regulatory requirements but also better aligned services with passenger needs throughout the day.

In addition to regular operations, HTM must also provide transport during rail replacement services and major events. These situations often require additional capacity and operational flexibility. Previously, two standard buses were typically needed to accommodate passenger demand during rail replacement operations. With the introduction of articulated buses, a single vehicle can now often meet this demand, reducing operational complexity and the number of drivers required.

Furthermore, HTM no longer needs to operate additional short-notice reinforcement trips, previously referred to internally as 'prikritjes', to meet peak passenger demand. These targeted extra services were costly and inefficient, as they required the sudden deployment of an extra bus and driver to relieve overcrowding. Thanks to the increased capacity of articulated buses, such measures are now largely unnecessary, resulting in a more efficient and predictable service delivery across the network.

In terms of operational costs, HTM noted that the shift to articulated buses has reduced the number of vehicles required to maintain regular service. However, the transition to electric buses has increased the need for drivers, as charging schedules and vehicle rotations introduce new planning constraints.

Finally, HTM indicated that the rollout of the articulated buses is being carried out gradually to ensure that all initial issues are addressed, enabling a smooth and well-managed transition.

B.0.2. GVB - Amsterdam

GVB – Amsterdam The Amsterdam Transport Region consists of three concession areas: the Amsterdam concession, operated by GVB; the Amsterdam Meerlanden concession (including Schiphol), operated by Connexxion; and the Waterland concession (covering Zaanstreek and Purmerend/Volendam), operated by EBS. GVB is responsible for public transport services within the Amsterdam concession.

GVB differentiates between two categories of lines. Some lines must operate at a minimum frequency of four buses per hour, as stipulated in the service specification (programma van eisen). On these lines, passenger demand would only require two buses per hour, and GVB deploys standard buses. On other lines with structurally higher demand, articulated buses are used to avoid the need for further frequency increases. This internal distinction supports a clear operational strategy: some lines are designated for standard buses, others for articulated vehicles.

According to GVB, operating a mixed fleet has limited impact on network efficiency. This is due to the clear division between lines based on service obligations and capacity needs. Half of the fleet consists of standard buses, and the other half of articulated buses, allowing the network to remain operationally balanced. As a result, GVB reports that the partial fleet composition does not cause significant inefficiencies.

Although articulated buses entail higher operational costs (due to energy use and depreciation), GVB reports that daytime demand remains high—partly driven by tourism and day-trippers. This justifies the continued use of articulated vehicles throughout the day, beyond traditional peak periods.

GVB did encounter infrastructure limitations on two lines where articulated buses could not be deployed due to restricted turning space. However, bus stop infrastructure across the rest of the network proved sufficient or was easily adapted. Although the turning radius of articulated buses is only slightly larger than that of standard buses, this small difference can be a decisive factor in some locations.

GVB has installed charging points at the termini of all articulated bus lines and additional locations throughout the city, including train stations. The operator takes every opportunity to charge buses, even during short layovers of five minutes at terminal stops. This strategy has so far ensured that no additional buses are required for charging-related downtime, compared to operations with diesel buses. In future, GVB may consider allowing buses to charge near the depot during service if they already pass nearby, which would increase flexibility and mitigate potential fluctuations in local charging capacity. GVB acknowledges that charging at terminal stops is the most efficient approach, as it minimises non-revenue kilometres and avoids return trips to the depot. Nonetheless, a small number of additional buses are still required to support the charging regime.

GVB also reported an increase in so-called slipping—where drivers switch buses during their shifts rather than remaining on a single vehicle. While efforts are still made to keep drivers with the same bus where possible, vehicle changes now occur more frequently, particularly when drivers take breaks. After completing a route cycle, buses pause for two minutes for schedule reliability, while drivers receive an additional three-minute break for personal needs. Since the bus itself does not require such a pause, GVB sees slipping as a way to optimise vehicle usage. During peak hours, drivers often do not receive a personal break and continue driving after the two-minute layover. Although drivers have expressed reluctance towards slipping, GVB considers it increasingly necessary for efficient operations, particularly on high-frequency routes, and especially under electric and articulated conditions.

In terms of energy consumption, articulated buses consume more than standard buses—approximately 2.0 kWh/km in winter compared to 1.4 kWh/km. However, articulated buses are equipped with larger battery packs (400 kWh versus 300 kWh). While standard buses have a slightly longer range, both vehicle types require interim charging. Since standard buses operate at lower frequency, they tend to benefit from longer charging breaks. GVB notes that the shorter range of articulated buses has not posed significant challenges but does require additional measures, such as more frequent charging or the use of dedicated 'charging buses', that are extra buses which can be used when too many buses are on too low battery. Although deploying such reserve vehicles incurs additional costs, GVB indicates that these are offset by savings on fuel costs compared to diesel buses. Overall, the transition to articulated electric buses has not required major changes to operational strategies.

GVB also highlighted the issue of localised peak demand. In some cases, high passenger volumes are concentrated in just one or two stops during a narrow time window. Despite low average occupancy, capacity planning regulations require that buses operate at no more than 60 percent of crush load capacity (i.e., a 104-capacity bus may carry just over 60 passengers). This planning constraint is based solely on the busiest point along a line, even if passengers disembark shortly afterwards. GVB considers this a topic that requires ongoing dialogue with the public transport authority.

The use of articulated buses enables GVB to save on staffing costs, as fewer drivers are needed compared to operating standard buses at higher frequencies. Situations in which passengers cannot board due to overcrowding are rare and typically only occur during major disruptions or events. However, GVB has reported localised crowding problems near some secondary schools. GVB acknowledges that operating with excess capacity is not cost-efficient. However, this is less problematic with electric articulated buses than with diesel vehicles. Electricity costs are relatively low, and fuel consumption is a significant cost factor for diesel operations. Although maintenance and depreciation costs remain relevant, they are considered less impactful. GVB stated that it is difficult to quantify exactly how much more expensive articulated operations are, but they emphasise that the largest portion of operating costs lies in staffing—which is unaffected by vehicle size.

Deploying articulated buses on a single line only is considered inefficient, as it results in disproportionately high maintenance and reserve fleet costs. Therefore, GVB avoids operating small sub-fleets wherever possible.

Finally GVB mentions that articulated buses were originally seen as a cost-saving measure, GVB now also considers them a solution to driver shortages. The operator has previously experienced a shortage of maintenance staff, which led to a higher number of buses being out of service. This, in turn, reduced overall fleet availability.