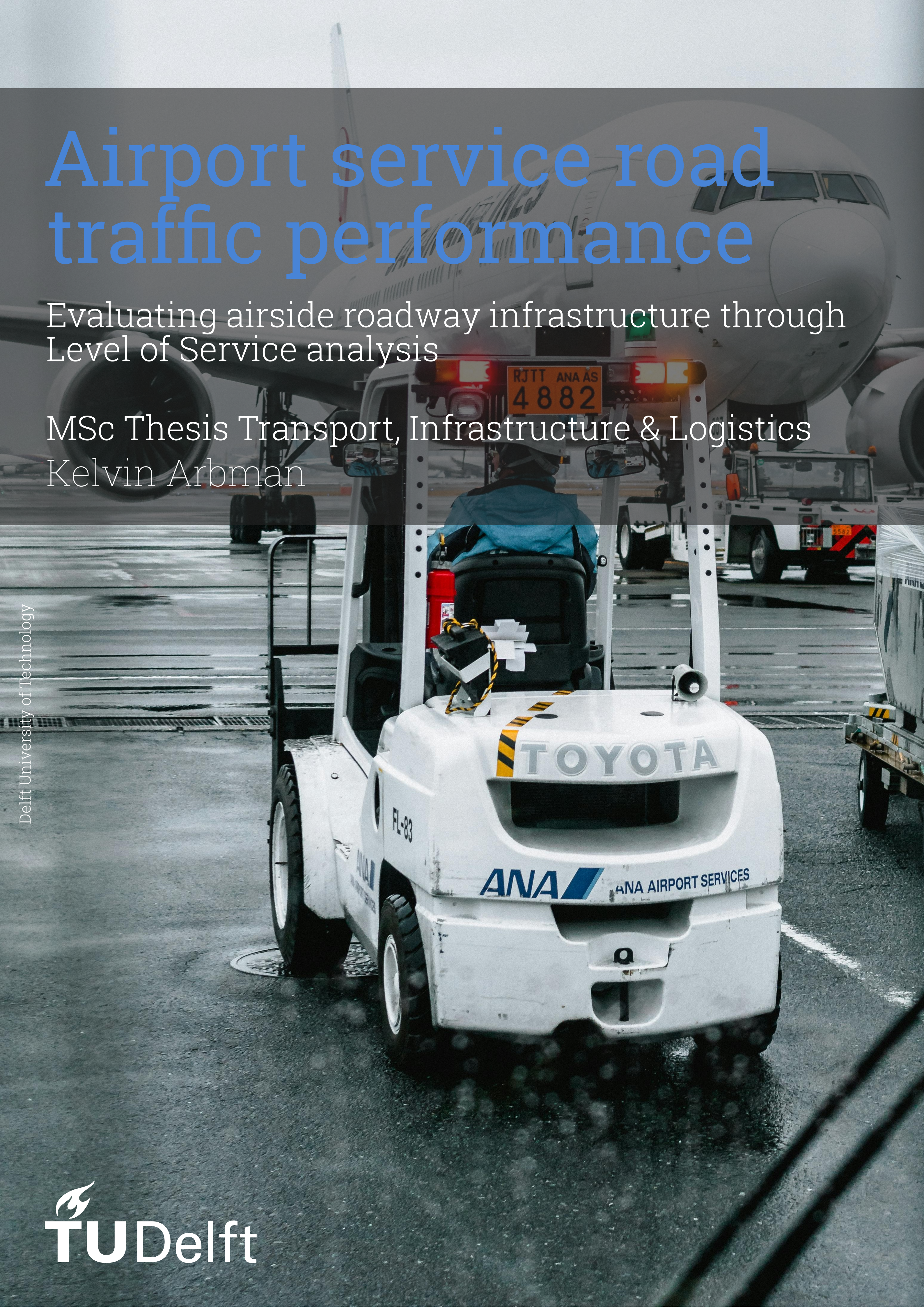
Airport service road traffic performance

Evaluating airside roadway infrastructure through Level of Service analysis

MSc Thesis Transport, Infrastructure & Logistics

Kelvin Arbman



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by

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Preface

This thesis is submitted in partial fulfilment of the requirements for the Master degree of Transport, Infrastructure & Logistics at the Technical University Delft. This degree and thesis were completed at the faculties of Civil Engineering and Geosciences (CEG), Technology, Policy, and Management (TPM), and Mechanical, Maritime & Materials Engineering (3ME). The thesis project has been developed in collaboration with NACO, Royal HaskoningDHV.

I would like to extend my sincere appreciation to the individuals who have contributed to the successful completion of this thesis. In particular, I would like to extend my heartfelt thanks to my main supervisor, Victor Knoop, for his support throughout the entire process and for his enthusiastic and invaluable feedback. I would also like to thank my co-supervisor, Alessandro Bombelli, for evaluating my work from an aviation perspective, which added the necessary nuance and enhanced the quality of my research. I would like to express my gratitude to NACO and team Airport & Strategy - especially to company supervisor Stefan Klomp - for offering me the opportunity to undertake this assignment and for their support throughout the process. Finally, I would like to express my heartfelt appreciation to my family and friends for their unwavering support and encouragement, not only throughout this thesis project but during my entire educational journey at TU Delft.

Kelvin Arbman
Delft, March 2025

Summary

Air travel is experiencing rapid growth, with an estimated annual increase of 3.4% in passenger numbers over the coming decades [6]. This expansion places significant strain on airports, which highlights the need for improvements in operational efficiency to accommodate rising demand. While much research has been conducted on optimising terminal operations, aircraft turnaround processes, and landside infrastructure, airside service road networks remain an underexplored aspect of airport performance analysis. These service roads play a crucial role in facilitating ground operations by enabling the movement of a diverse range of vehicles that service aircraft during turnaround times. Despite their significance, there is currently no standardised method to evaluate their performance effectively.

This research is driven by the increasing need to evaluate and enhance airside service road networks, especially at large airports where congestion is becoming a relevant issue. Unlike conventional roadway networks, airside service roads accommodate a highly heterogeneous mix of vehicles, each with distinct physical and behavioural characteristics. These vehicle types include, among others, baggage trains, fuel trucks, catering trucks, cleaning vehicles, and aircraft push-back tractors. The high degree of traffic heterogeneity complicates traditional traffic analysis methods, and requires a tailored approach to performance evaluation of service roads.

This study aims to develop a methodology for assessing airside service road performance by adapting concepts from conventional road capacity analysis. One of the key methodologies employed in this research is the Passenger Car Unit (PCU) analysis, which quantifies the impact of different vehicle types relative to a standard passenger car. Since airside vehicles show significant behavioural differences from passenger cars, determining their PCU values allows for a more accurate representation of their influence on road capacity. Once PCU values are established, the study conducts capacity analysis by simulating oversaturated traffic conditions to determine the maximum sustainable hourly flow of vehicles. These capacity estimates, expressed in PCU per hour, provide insight into the critical thresholds at which different infrastructure components become congested. Finally, the study applies the Level of Service (LoS) classification, commonly used in the Highway Capacity Manual (HCM) [58], to categorise traffic conditions into six levels, ranging from A (optimal conditions, low delay) to F (unstable conditions, high delay). This classification is applied to airside service roads to establish benchmarks for acceptable performance under varying traffic conditions.

To achieve these objectives, a multi-stage research methodology was developed, combining microscopic traffic simulation with statistical analysis. The study begins with a system-level analysis of airside service road networks, identifying common infrastructure components. Observations from multiple large airports informed the selection of key roadway elements for analysis. Ultimately, it was decided to include the following infrastructure components: four-way priority intersections, four-way roundabouts, three-way priority intersections, three-way alternative intersections, and main road segments connected to aircraft stands. The next phase involves constructing microscopic simulation models using PTV VISSIM 2023 [23], a widely used traffic simulation software capable of capturing individual vehicle movements and interactions. A simulation model is made for each infrastructure component mentioned.

The simulation models incorporate a representative mix of airside service vehicles, which is estimated based on typical aircraft compositions and stand compositions using real-world airport data. The simulations generate travel time data, which are then transformed into a total delay for an entire simulation run based on the optimal travel time for each vehicle type. Total delays are subsequently used for multiple linear regression analysis to estimate PCU values. The regression model uses total delay as the dependent variable and the vehicle composition (number of vehicles per service vehicle type) as the independent variable, which allows for the quantification of the impact of each vehicle type in terms of PCU.

To validate the applicability of these findings at a broader scale, the study extends the analysis from

individual roadway components to a network-level evaluation. A representative airside service road network is constructed, which incorporates typical design elements found in large-scale international airports. The network-level simulations assess overall performance by aggregating LoS results across multiple intersections and road segments. This holistic approach ensures that the methodology can be applied to diverse airport environments, rather than being limited to a single case study.

The results demonstrate that service road performance is highly dependent on vehicle composition and infrastructure design. Slow-moving and large vehicles, such as baggage trains and fuel trucks, contribute substantially to congestion, particularly at priority-controlled intersections. Roundabouts, in contrast, tend to support heterogeneous traffic flow more effectively, which reduces the likelihood of excessive delays. The PCU analysis highlights the extent to which different vehicle types impede throughput, revealing that certain service vehicles have a much higher impact on capacity than others. The findings indicate that while LoS assessment provides a useful performance metric, it must be interpreted within the context of airside-specific traffic conditions, rather than being directly replicated from conventional road systems.

These insights highlight the importance of incorporating service road performance evaluation into airport planning and expansion projects. Given the expected increase in air travel demand [6], airports need to consider service road capacity alongside other critical infrastructure developments. By understanding the relationship between traffic heterogeneity and delay, airport planners can evaluate service roads more effectively.

In conclusion, this research provides a standardised methodology for the evaluation of airside service road performance using PCU analysis, capacity estimation, and LoS classification. By adapting established traffic engineering principles to the unique characteristics of airport environments, this study contributes to bridging a critical gap in airside infrastructure performance evaluation. The proposed framework offers a structured methodology to assess airside service road performance, enabling airport operators and planners to identify capacity limitations and estimate vehicle delays within the network. While the study establishes a strong foundation, future research is recommended to refine the methodology by incorporating real-world vehicle tracking data, as well as testing the applicability of the developed framework at various international airports to enhance its robustness and generalisability.

Contents

1 Introduction

The forecasted 3.4% annual increase in air travel in the coming decades [6] doubles the demand for airports by 2040, which is expected to intensify the pressure on airside facilities and operations. Without improving the efficiency of airports, this growth will be limited, and the aviation industry loses momentum [18]. Ground operations will need to adapt to this fast-growing demand by further optimising available resources, including baggage and passenger handling, fuelling, servicing and aircraft maintenance. These services play a crucial role in the turnaround time of an aircraft, which greatly contributes to the competitive advantage of airports and airlines [27].

An important but often overlooked part of the airside infrastructure is the service roadway system. Service roads are used to feed aircraft on the airside of an airport with service vehicles, which are critical for an efficient and timely turnaround. These roads are used by a large variety of vehicle types with different physical and behavioural characteristics. As airports are growing, the stress on service road increases and they are becoming more congested during peak hours. It is crucial to understand the performance of this airside infrastructure, as this can have a great impact on the timely departure of aircraft.

1.1. Context

The current problem that the aviation industry is facing is that there is no clear method available to determine the performance of service roads in particular. Airport projects with large projected increases in terms of annual passengers require an extensive review of the service road system, as they want to know if their current infrastructure is sufficient to fulfil future demand. There is a comprehensive method developed on how to model and assess traditional roadway infrastructure used for accessing the airport [57], but a similar method for airside service roads has not been found in the literature.

Although airside service road systems often have simple layouts, the underlying operations that govern vehicle movements are highly complex. This complexity results in a diverse range of system users, leading to significant traffic heterogeneity on airside service roads. The traffic participants exhibit substantially different behaviour, which is caused by differences in speed, acceleration, deceleration, size, and manoeuvrability. This greatly influences the performance of the road system and complicates the calculation on operational performance. Therefore, it is crucial to accurately represent the varying traffic mix and develop a method that can appropriately express the differences in vehicle characteristics for airport service roads. A lot of research has been performed on methods capturing traffic heterogeneity [2, 43, 53, 48], but none are applied to airside service roads in particular.

Additionally, prior literature review (which is described in Chapter 2) has concluded that while research has extensively covered individual ground handling procedures, there is a notable lack of attention to the infrastructure that supports the movement of ground handling vehicles. The Airport Cooperative Research Program [49] has also noted a lack of traffic studies performed by airports for service roads specifically, even though expansions and improvements of service road systems are being considered.

However, numerous studies have concentrated on the performance of urban intersections and other conventional roadway infrastructure. An important document that describes this is the Highway Capacity Manual (HCM) [58], and it measures the performance of roadway systems using a Level of Service (LoS) metric, which is also a commonly used metric within the aviation industry as well for determining the performance of various airport systems and infrastructures. The HCM qualitatively divides the performance of roadway networks into six distinct levels from “A” to “F”, where LoS “F” represents the worst possible performance. Additionally, various methods have been developed to capture traffic heterogeneity on traditional roadway systems, such as measuring the Passenger Car Unit (PCU) for each vehicle type. This approach determines the influence per vehicle type by comparing it to the performance of a standard passenger car.

1.2. Research objectives and scope

This research aims to assess the capacity and performance of service road infrastructure components (i.e. intersections or segments). Microscopic simulation models specifically designed for evaluation of (roadway) traffic systems are to be made, which are able to assess the results, from a traffic engineering perspective, to a higher standard compared to current methods being used within the aviation industry. Moreover, traffic heterogeneity should be captured accurately within this analysis. Another key objective of this research is to develop an evaluation methodology that is widely applicable to various airports, rather than being tailored to a specific location. Furthermore, this research aims to provide a comprehensive framework on how service roads can be evaluated on network-level by providing an example study of a representative service road (sub-)system.

This research focuses specifically on airside service road systems. The system analysis will not encompass terminal areas or related processes like baggage handling and passenger boarding in detail, but vehicle-movements that are a result of these processes are of importance. Also, the arrival and departure of aircraft during peak hours is taken into consideration for the generation of service vehicles, but the actual movement of aircraft and conflicts with service road users will not be considered. Other non-vehicle related movements such as pedestrians are also outside the scope of this research. This research will focus on larger airports (20+ million passengers per year), since these are primarily at risk of being subjected to oversaturated service roads. Infrastructure components that adequately meet the demand for the service movements of even the largest airports are also not considered.

1.3. Research questions

Given the problem outlined in this introduction and a literature review (Chapter 2), the following main research question has been formulated:

How can the performance of airside service roads be estimated using a standardised method that is applicable to various airport environments?

The main research question is supported by the following sub-research questions:

1. How can the performance of individual infrastructure components of airside service roads be determined?
    - (a) Which commonly present infrastructure components need to be modelled and analysed?
    - (b) What are the Passenger Car Unit values of the airside service road vehicles for each infrastructure component?
    - (c) What is the capacity of the infrastructure components in terms of Passenger Car Unit per hour?
    - (d) What are the boundaries of different Levels of Service (A-F) of the infrastructure components, expressed in Passenger Car Unit per hour?
2. How can the results from the analysis of individual infrastructure components (research question 1) be upscaled to a network-level model?
    - (a) How can the Level of Service of an entire service road network be expressed?

(b) Are the boundaries of different Levels of Service (A-F), expressed in Passenger Car Unit per hour, found in this research applicable to service road networks?

(c) How does a representative airport service road network perform when evaluated using the analysis methods established in this research?

The research questions for this master thesis are structured to ensure a comprehensive analysis of airside service roads, starting from individual infrastructure components and extending to a network-level model. This hierarchical organisation of research questions facilitates a systematic approach to this study, which enables a thorough examination of the different aspects of airside service road networks.

The first set of sub-research questions focuses on the performance of individual infrastructure components of airside service roads. This is broken down into specific sub-questions that address the modelling and analysis of commonly present infrastructure components, the determination of PCU values for each component, the capacity of these components in terms of PCU per hour, and the establishment of boundaries for different service levels (A-F) expressed in PCU per hour. These sub-questions are logically sequenced, and build on one another to provide a detailed understanding of each component's performance.

The second main research question explores how the results from the analysis of individual infrastructure components can be upscaled to a network-level model. This includes expressing the LoS for an entire service road network, assessing the applicability of the PCU per hour boundaries found in the research to service road networks, and evaluating the performance of a representative airport service road network using the established analysis methods provided in this research. This set of sub-questions ensure that the findings are not limited to isolated components but are applicable to real-world networks, which enhances the practical relevance of the research. The logic behind the structuring of the research questions will be explained in more detail in Chapter 3 (Methodology).

1.4. Report outline

This report is structured to systematically address the research objectives. First, a literature review is presented in Chapter 2. Chapter 3 describes a high-level methodology that is to be applied in the following chapters. In Chapter 4, a system analysis on service roads is performed to highlight relevant factors that need to be considered during the modelling phase of this research. The traffic simulation model input is presented and discussed in Chapter 5. The component-level analyses start with a calculation of the PCU values, which is reported in Chapter 6. Hereafter, the capacity of individual infrastructure components are determined in Chapter 7. The component-level part of this research ends with a LoS determination, which is reported in Chapter 8. The findings of these analyses are upscaled to a network-level model in Chapter 9. Lastly, the conclusion and discussion of this research are presented in Chapter 10.

2 Literature

2.1. Review methodology

The literature review will be based on scientific articles found through search engines Scopus, Google Scholar and Consensus, using keywords presented in table 2.1. These are categorised in three main subcomponents: Passenger Car Unit, Highway Capacity Manual and traffic flow modelling. The concept of PCU is examined to gain a deeper understanding of traffic heterogeneity and the various methods discussed in the literature for capturing it. The principles and indicators of the HCM are analysed, after which applications from the literature are reviewed. Traffic flow modelling techniques and software are also studied in this literature review.

Table 2.1: Keywords Literature Review

Concept Groups	**Keywords**
Passenger Car Unit	PCU, PCE, methods, indicators, traffic heterogeneity
Highway Capacity Manual	Application, delay, volume, capacity, performance, level of service
Traffic flow modelling	Simulation, aggregation level, traffic modelling software

2.2. Passenger Car Unit

Research has found that speed, size, acceleration capability, and manoeuvrability are important indicators for PCU estimation [16]. Due to the variation in these factors among service road users included in this study, it is anticipated that different vehicle types will significantly impact infrastructure performance and limit the capacity in terms of vehicles per hour. Research on service road systems at Amsterdam Schiphol Airport [15] has shown that there is indeed a large variety of users, each with different physical and behavioural characteristics. Although the maximum speed on airport service roads is generally around 30 km/h [49], the Schiphol Airport case study revealed that many vehicles commonly deployed at airports are limited to speeds of approximately 15 km/h. Combined with the large footprint of these vehicles, this traffic heterogeneity significantly impacts traffic performance.

In the literature, PCU, also referred to as Passenger Car Equivalent, is often used to compare the impact of different vehicle types on traffic performance indicators such as delays, travel time, or travel speed [58]. Comparative analysis of methods for estimating PCU values on unsignalised intersections [42] suggests three alternatives for PCU estimation: based on occupancy time, capacity or queue clearance rate. Each method compared in this research provided logical and representative PCU values.

However, a literature review of methodologies for PCU analysis [52] has revealed inconsistencies in the resulting PCU values across different methods, highlighting the importance of choosing the most appropriate method. Research on highly heterogeneous conditions [2] has concluded that Multiple Linear Regression (MLR) is especially appropriate when traffic is subjected to large variations in physical and behavioural characteristics, which indicates its potential for airport service road systems. An application of this method on urban intersections [53] has concluded that MLR is effective, efficient, and appropriate for estimating PCU values under heterogeneous traffic conditions. This research was conducted in the Indonesian city of Banda Aceh, where roads are subjected to a large variety of vehicle users: motorcycles, passenger cars, motorised rickshaws, and different-sized trucks and buses. Despite its value for determining PCUs under these conditions, the degree of heterogeneity on airport service roads is even more intense.

Comparative studies of PCU estimation methods by Mondal et al. [43] and Raj et al. [47] have also acknowledged that MLR is one of the most useful techniques for determining PCU values at intersections. Various implementations of MLR applied to roadway systems to obtain PCU values exist in the literature. Research analysed [43, 47, 53] uses the number of vehicles of each vehicle type i as independent variables for the MLR model. An advantage of this method is that it can compare the regression coefficients of each vehicle type directly with each other.

The choice of the dependent variable varies and mostly depends on the focus of the study. Highway applications are often modelled using Free Flow Speed, while in urban environments and intersections, it is more useful to calculate the experienced delay, as indicated by the Highway Capacity Manual [58]. PCU estimations based on delay by Raj et al. [47] allow for computing the delay experienced by one driver as the difference between the delay of a vehicle i and the "base" delay, which is considered the delay of the reference vehicle (passenger car).

2.3. Highway Capacity Manual

2.3.1. Principles of the Highway Capacity Manual

HCM is a general guide created by the Transportation Research Board [58] for transportation engineers and researchers which provides a set of methods to evaluate the performance of highways and urban roads. It analytically measures six different degrees of Level of Service (LoS), A to F, where level "A" represents the best performing design.

LoS is a well-known performance metric within the aviation industry which quantitatively assesses various airport and terminal facilities, based on the provided service for its users (International Air Transport Association, 2021). The LoS framework created by IATA [29] only considers passenger services in the terminal building of an airport, for instance departure/arrival halls, check-in areas, security control, baggage reclaim, etc. However, using the principles of HCM, an application of the LoS-concept is created specifically for landside public roadway systems by the Transportation Research Board [57]. This method is also used by traffic engineers within the aviation industry to make solid estimations about the accessibility of public landside roads.

The HCM is a general framework that describes how different modes of transportation can be analysed on operational, design, preliminary engineering and on planning level. It focuses primarily on automobile-systems, with varying levels of traffic heterogeneity. Traffic systems including both uninterrupted- and interrupted-flows can be incorporated into the analysis. They divide each system into points, segments and facilities. The definition of a point is a location inside a facility where traffic crosses, merges, diverges, is regulated by a traffic sign, or influenced by a changing road layout (e.g. lane drop or addition). Segments are defined as a section of a roadway between two points. A facility is a collection of connecting points and segments belonging to the same road type. [58]

2.3.2. Application of Highway Capacity Manual

Example studies of a direct application of the HCM on airside service roads have not been found in the literature. However, analysing the fundament of this traffic theory in combination with applications of HCM to other roadway systems could provide useful information for airside road systems. The following analysis is based on the HCM of 2010 [58].

HCM defines a set of common facilities, specifically freeways, multilane highways, two-lane highways, and urban streets for the automobile system. For the case of airport service roads, which are made from short segments of mostly one-lane roads (both directions), following the HCM framework these would identify as urban roads. Due to the lack of applications of HCM for service roads, only key elements of its framework can be used for analysis.

Percentage Free Flow Speed (PFFS) calculation is a fundamental aspect of HCM's application to urban road networks. PFFS is described as the average chosen velocity of a vehicle when it is not influenced by traffic streams or traffic control measures [40]. Early evidence by Lamm et al. [36] has shown that road geometry, (structural) conditions, characteristics of driver behaviour and the environment are main factors in determining PFFS. Empirical evidence from Saifizul et al. [51] also suggests that the higher average weight of vehicles on roads should be considered when determining the performance of a roadway system. Their analysis revealed a negative correlation between vehicle weight and both the mean and variance of PFFS. This is an important notion for the application to service roads, as the average weight of the ground handling vehicles is significantly higher compared to traditional road conditions. These notions do however not only apply to PFFS, but roadway performance in general.

Alternative indicators such as volume-to-capacity ratio [14] or delay [47], can also be chosen. Both are also considered by the HCM. The HCM states that volume-to-capacity ratio is more applicable to uninterrupted flow, while interrupted flow segment (including intersections) can better be modelled using delay [58]. An additional advantage of using delay compared to PFFS is the complexity to retrieve real-life data, as shown by video-based data collection analysis of Indian urban roads and subsequent LoS-analysis [46]. The complexity potentially increases significantly when accounting for the high level of traffic heterogeneity on service roads, as this method compares the actual travel speed with the optimal travel speed, which varies depending on the different vehicles classes.

2.4. Traffic flow modelling methods

To accurately capture the airside service roads and its underlying operations, the benefit and application of traffic flow modelling methods will be analysed. This literature analysis dives into the different levels of aggregation, as well as the different (commercial) simulation tools that are available and appropriate to analyse the issue.

2.4.1. Aggregation level

Various traffic flow modelling approaches exist within the literature, each with its own level of detail. The appropriate level of detail depends on the specific goals of the model. Within traffic flow modelling, there are generally three main categories: macroscopic, microscopic and mesoscopic simulation. Macroscopic modelling offers the highest level of aggregation. It focuses on the overall flow of traffic over time, using macroscopic variables like density, volume, and average speed. Microscopic has the highest level of detail, as it projects the motion of each individual vehicle within the traffic flow. A mesoscopic model shares many attributes of microscopic models, but generally some simplifications are made to reduce computation times. [7]

To achieve a comprehensive understanding of airport service road operations, microscopic modelling will be employed to replicate the interactions between vehicles, infrastructure, and dynamic traffic conditions. Although the design of service roads may be relatively simple, the behaviour of individual vehicles are not. The Transportation Research Board [57] considers airport systems to be sufficiently complex to justify the use of microscopic simulation. Additionally, compared to current traffic models used by within the aviation industry, improvements with respect to traffic flow modelling are needed to produce better insights on the performance of the airside system. Realistic car-following, queueing and mix traffic theory need be applied to determine the capacity of service roads more accurately. This can be achieved only through microscopic modelling.

Earlier research on the airside service road system of Amsterdam Schiphol Airport by De Jong [15] has presented the potential of microscopic simulation applied to service road systems. It was able to analyse different service road pier designs and compare them based on their level of robustness and safety. Microscopic modelling techniques are also frequently applied to urban roads and intersections [26, 54], which have substantial similarities with airside service roads in terms of road layout.

2.4.2. Simulation software

This section focuses on the different available simulation software packages. Only software from which a license can be obtained (via TU Delft or external parties) are considered.

CAST
There are various options for modelling traffic systems. A frequently used simulation software within the aviation industry for modelling various aspects of an airport, including landside, terminal and airside operations, is CAST. There is a specific module available for vehicle ground handling [4]. The advantage of this simulation package is that it can be integrated with other airport-related systems. Additionally, it is also able to incorporate the underlying functioning of ground handling services.

However, CAST is not as extensive on investigating traffic engineering-related issues as some of the other alternatives. Another issue that has been identified when experimenting with this software is the queueing of vehicles on two connecting road segments, as they appear to be stacking in case of congestion. This would lead to inaccurate estimations of the capacity of such systems. Because of the solid interaction with other airside systems, retrieving data from CAST simulations can potentially be useful in future studies.

PTV VISSIM
PTV VISSIM is a commercial software package for microscopic traffic simulation. While primarily used for urban traffic, it can also be adapted to model traffic on other types of infrastructure. It offers various extensions for specific applications, allowing users to customise the software to their needs. Apart from traffic flow, it is also able to incorporate traffic control strategies for signalised and unsignalised intersections. PTV provides also provides an extensive manual [45] and online support. VISSIM can integrate various types of service vehicles with different characteristics, enabling it to accurately capture traffic heterogeneity.

Challenges may arise when integrating other relevant ground handling systems. The generation of trips is dependent on the arrival of aircraft and the tactical deployment of service vehicles, and research on the interactions between these systems and the service road infrastructure is very limited. Simplifications of the model might be necessary when developing the model. Another challenge is the incorporation of service road vehicles. Each having unique behavioural characteristics, this would require further analysis to gain valuable insights. Previous research where PTV VISSIM was used for modelling service roads [15] has implemented all service vehicles needed to serve the aircraft, but only in terms of physical input parameters such as speed, length and turning radius were included. Further literature research is needed for specific behavioural adaptations of the vehicles.

SUMO
Simulation for Urban Mobility (SUMO) is an open-source microscopic traffic simulator. As it is a similar type of software package as PTV VISSIM, it shares many of the benefits. The extra benefit of SUMO is that one does not need to purchase a commercial license to use it. A comparative analysis by Maciejewski [39] has indicated that the simulation speed of the model is slightly higher than PTV VISSIM's.

The research by Maciejewski [39] also indicates that PTV VISSIM more accurately simulates vehicle dynamics compared to SUMO. Simulations between both have shown that SUMO structurally underestimates road-capacity. Additionally, compared to VISSIM the variety of applications in SUMO seem to be lacking. There is also more modelling support available on the internet for PTV VISSIM.

2.5. Conclusion & discussion literature review

While research has extensively covered ground handling procedures, there is a notable lack of attention to the infrastructure that supports the movement of ground handling vehicles. As airports expand, the stress on service roads increases. Understanding what influence this has on the capacity and performance of existing infrastructure is crucial for determining whether it can support future growth. Traffic engineering related studies on this subject are present, such as the case study of Amsterdam Schiphol Airport [15], but there is a desire from the aviation industry to have a framework on determining performance that can be universally applied. This has not been found in the literature.

The literature study has highlighted the importance of speed, size, acceleration, and manoeuvrability in estimating PCUs for airport service vehicles [16]. Due to the diverse characteristics of these vehicles, they significantly impact infrastructure performance and capacity. MLR is identified as an effective method for PCU estimation under heterogeneous traffic conditions [2]. The literature study has emphasized the need for tailored PCU analysis to accurately assess traffic performance on airport service roads, considering the unique mix of vehicle types and their operational constraints.

This review has also explored the possible application of the Highway Capacity Manual on airside service roads. Although the manual has been widely used in the literature on different subjects other than urban and highway roadway systems, there has been no specific application to service roads. Therefore, a comprehensive analysis on how the manual's principles apply to service roads is necessary. While key aspects of the methodology appear applicable, adjustments may be needed to create a realistic framework.

Different simulation software has been considered within this review. Based on the arguments mentioned in section 2.4.2 (simulation software), a decision has been made to choose PTV VISSIM. The primary logic behind this decision is its broad application possibilities, and widely available support for various modelling tasks. Furthermore, it is able to capture the traffic heterogeneity present on airport service roads accurately.

3

Methodology

3.1. Overview

Similarly to the structure of the research questions, the methodology of this research has been divided into two parts: component-level and network-level modelling. The component-level modelling part, where infrastructure elements (i.e. different types of intersections or segments) are analysed individually, has provided answers to the first set of research questions presented in the introduction. These analyses are described, reported and discussed in Chapters 6 (PCU), 7 (capacity) and 8 (LoS). It has been followed by a network-level modelling part, where the findings of the component-level modelling are upscaled to a representative, fictional airport service road system (Chapter 9).

A schematic overview of the entire research methodology has been presented in Figure 3.1. As can be seen in the legend on the top of the figure, this part of the research has been divided into six subparts. First, an analysis of service roads has been performed (Chapter 4), giving general insights on the airside service road infrastructure that is modelled in the subsequent stage. In this subsequent stage, traffic simulation models of the infrastructure components are created and simulated that serve as a basis for the analyses that follow. The quantitative output from the traffic simulation model is then used for the PCU (Chapter 6), Capacity (Chapter 7) and LoS calculations and determinations (Chapter 8). A further explanation for the logic of this methodology will be given in Section 3.2.

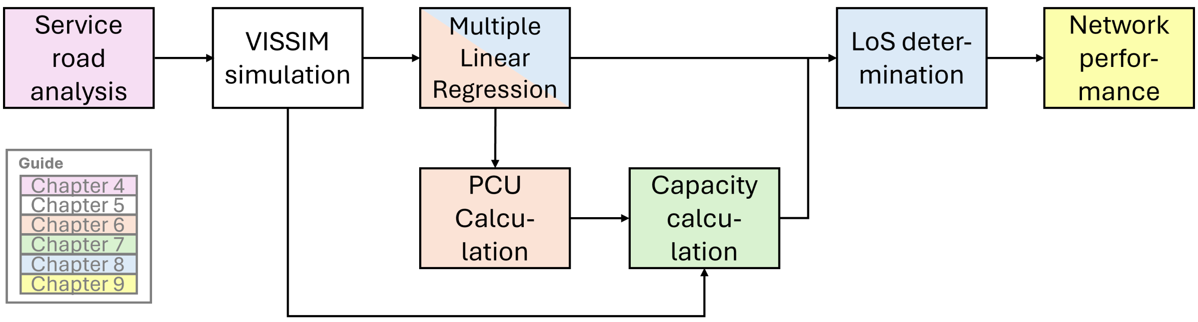


Figure 3.1: Research methodology and reading guide

The network-level modelling (Chapter 9) aims to provide a framework based on the findings of the component-level analyses for evaluating the performance of service roads on a network-level. The network model is also used to validate the findings of the component-level analyses by testing them on a larger system, incorporating operational demands. Lastly, the performance in terms of LoS of a representative network is assessed using the methodology that is described in this research.

Research typology

This study is primarily based on quantitative research resulting from traffic modelling and simulation. This has allowed for precision, objectivity and replicability that is needed to analyse individual infrastructure components of service roads, as well as testing the findings on a network-scale. Quantitive data are extracted from the models and used as input for further analyses.

However, these analyses are supplemented with qualitative research as well. A qualitative system analysis is executed to obtain relevant knowledge on the design, operations and requirements of service road systems. Additionally, while calculations supporting the LoS determination are a result of quantitative data, the actual interpretation of the concept of service from a user-perspective is characterised as a qualitative research application [58].

3.2. Research design

This section describes the overall framework of the research. For each of the six sub-parts outlined in Figure 3.1, a high-level explanation will be provided regarding their execution and how each element interrelates to form a cohesive framework. A more in depth description including mathematical formulations, input data, model parameters and experiment setups will be explained in the corresponding Chapters (see legend).

3.2.1. Service road analysis

A service road system analysis has served as a crucial first step in understanding service roads in general and what thrives traffic performance on these networks. Characteristics and relevant input on the design of service roads and its users are gathered. Furthermore, it has selected the infrastructure components essential to general airside service roads, which are included in further research stages. Therefore, it has effectively answered sub-research question 1(a). Service roadway infrastructure components are analysed and selected using Google Earth Pro [21], by studying the design of existing service road systems of large-scale international airports.

3.2.2. Microscopic traffic modelling

Since this is a simulation-based study where real-life data regarding service roads is lacking, identifying the most appropriate modelling method that can establish a foundation for addressing the research questions is essential. Furthermore, it is important that the simulation-based model is capable in providing insights that are applicable to various airport environments and is therefore not suited for one specific case study. The chosen traffic modelling method should be able to represent such a theoretical environment accurately and effectively.

A literature review (Chapter 2) has explored several aggregation levels: microscopic, macroscopic and mesoscopic traffic simulation. In conclusion, it was decided that in this case microscopic traffic simulation is deemed most appropriate for answering the research questions. Primary reason for this is that it should be able to capture the traffic heterogeneity present on airside service road systems accurately, as this is one of the major dissimilarities compared to traditional roadway systems. Microscopic aggregation level models simulate the behaviour of individual vehicles, their unique characteristics (speed, acceleration, deceleration, etc.) and the interaction between vehicles (car-following, priority giving, etc.), while in mesoscopic and macroscopic models the possibility for modelling such aspects are limited.

This part of the research in itself does not answer any research questions in particular. It does however serve as the primary data-collection method for the analyses in later stages. In next sections of this chapter, it will be explained how microscopic traffic modelling is used to support the analyses.

VISSIM

In the literature review (Chapter 2), multiple microscopic simulation packages have been considered. This includes airport-specific simulation software CAST [4], open-source package Simulation for Urban Mobility (SUMO) [20] and commercial package PTV VISSIM [45]. In conclusion, it has been decided to use VISSIM for the purpose of this research. It has widely been used for various applications within the traffic engineering discipline [39]. The software is flexible enough to represent a theoretical model specifically for airport service roads, as is also proved by a case study of Amsterdam Schiphol airport [15]. All functionalities are well-documented in the PTV VISSIM manual and the package is widely supported online for a wide range of modelling tasks. TU Delft owns a license that can be used for academic purposes. Version VISSIM 23 has been used for this research.

To create a representative environment in VISSIM, the most important and relevant infrastructure, vehicle and routing parameters are collected as much as possible. These are incorporated in all VISSIM models (component-level and network-level) created within this research. To obtain reliable results that are applicable to various environments, traffic compositions (distribution of vehicles) are varied. This is purposefully done to validate the results and to enhance the understanding for airport service roads in general, as the traffic composition on the infrastructure is unique for every airport. The model input used within this research are presented and discussed in Chapter 5.

VISSIM is able to extract relevant data relating to traffic engineering. The most important output that is being collected is the number of vehicles of every vehicle type and the travel time for each individual vehicle. The travel time is then used to calculate the total delay, which in turn is (along with the number of vehicles) relevant for the PCU, LoS and capacity analyses. After extraction of the results in VISSIM, data is transfered and analysed in more detail using Microsoft Excel Version 2412 [41] if necessary.

3.2.3. Passenger Car Unit analysis

The heterogeneous nature of service roads significantly impacts infrastructure capacity and performance [14]. To standardise the measurement of this impact, a PCU is used, which compares the influence of various vehicle types to that of a typical passenger car, which has a PCU value of 1 [58]. Key vehicle parameters that have influence on PCU include speed, size, acceleration and deceleration capability, and manoeuvrability [16]. These factors are incorporated into the VISSIM model and therefore represented in a realistic manner.

Multiple Linear Regression

This research employs VISSIM traffic simulation models to capture individual traffic behaviour and uses Multiple Linear Regression (MLR) for estimating PCU values under heterogeneous traffic conditions. Research on obtaining PCU values under heterogeneous conventional intersections by Sugiarto et al. [53] has shown that MLR is effective and efficient for estimating PCU values in similar contexts, supporting its use in this study. Additionally, literature review on different methods for estimating PCU values [52] has identified that MLR is specifically capable when there is a high degree of traffic heterogeneity present. For the MLR, statistical software package IBM SPSS Version 29 [28] is used to calculate the regression coefficients.

To obtain the vehicle-specific impact (expressed in PCU) on the performance and capacity, the regression coefficients of all vehicles are compared to the regression coefficient of the passenger car. VISSIM has created a highly precise model of a passenger car, capturing both its physical and behavioural characteristics. This model has been calibrated, optimised, and enhanced through over thirty years of applied traffic engineering research [45]. This validates the suitability of the simulation-based passenger car and its use for PCU calculations as a reference.

Different implementations in the literature use various independent variables for the MLR model, with the choice of dependent variable often depending on the study's focus [43] [47]. For this research, total delay of a simulation period is chosen as the dependent variable, which is also needed for the determination of the LoS. This ensures comprehensibility between the different analyses. The number of vehicles per vehicle type is used as independent variables, which allows PCU-calculation based on the regression coefficients.

Other than obtaining PCU values, the MLR in itself is a useful delay prediction model. When setting up the model as described, it can be used to predict the delay on a certain infrastructure component based on the number of vehicles of each type present during a certain time-period. Subsequently, this prediction model can be used to determine the LoS, which will be elaborated in section 3.2.5.

The PCU analysis detailed in this section has effectively standardised the heterogeneous traffic composition, making it potentially applicable to various airport environments. This analysis - which is described and reported in Chapter 6 - addresses sub-research question 1(b) (PCU values for each infrastructure component) and also contributes to answering overall research question 1 (performance of individual infrastructure components) by quantifying the relative performance of each vehicle type for specific infrastructure elements.

3.2.4. Capacity analysis

The capacity of the individual infrastructure components is calculated based on the number of vehicles that are being recorded during a simulation where the roadway is oversaturated, meaning that not one extra vehicle movement could be facilitated. Across twenty simulations, for every infrastructure component the average maximum output is recorded in terms of vehicles per hour, representing the maximum sustainable hourly flow. This is then transformed into a capacity in terms of PCU per hour, using the PCU values obtained in earlier phase of this research.

This analysis supports the answering of research question 1(c) (capacity of infrastructure components, expressed in PCU per hour). Capacity is also an important performance measurement for the performance of roadway infrastructure. From this analysis, useful information can therefore also be acquired for research question 1 (performance of individual infrastructure components) in general. The analysis is described and performed in Chapter 7.

3.2.5. Level of Service analysis

The LoS for intersections is determined based on intersection delay, following the HCM [58] guidelines. The MLR model discussed earlier in this chapter has provided a total delay prediction model, which is essential input for the determination of the LoS. The total delay is decomposed into intersection delay and platoon delay, with the latter being subtracted to isolate the intersection delay. A more detailed explanation is given in Chapter 8), as well the presentation of the results of this analysis.

Using the HCM, pre-described boundaries are formulated to distinguish different service levels for every infrastructure component. These are characterised from A-F, with LoS “F” being the worst performance. Additionally, if traffic volumes exceed the capacity of the infrastructure, this infrastructure is also assigned LoS “F”. Therefore, the capacity (expressed in PCU per hour) determined in prior analysis is critical input for this part of the research.

This method has enabled the estimation of LoS based on the number of vehicles passing the infrastructure component during a specific time interval, using the MLR prediction model. Therefore, an answer has been formulated for research question 1(d) (LoS boundaries expressed in PCU per hour). Additionally, this method has provided insights into the general performance of individual infrastructure components. By characterising each component with a qualitative assessment of the LoS, it has also contributed to research question 1 in general (performance of individual infrastructure components).

3.2.6. Network-level modelling and analysis

The chosen methodology for analysing the performance of service roads on a network-level utilises a micro-level approach in which the network is decomposed into individual segments or intersections, in a similar manner as is presented for the component-level modelling part. A theoretical service road network is designed following the common design practices for this airside infrastructure, which realistically represents a part of an airport environment facilitating 12 to 15 million annual passengers. Each component’s LoS is assessed using basic vehicle counts over small time intervals. The methodology aggregates these assessments over small time intervals of five minutes, and adjusts for traffic volume to ensure an accurate representation of network performance. Different cut-off percentiles, ranging from 95 to 100, are used to provide valuable insights for various airport environments, meaning that conclusions can be drawn that are not specifically tailored for this particular network. The methodology for network-level LoS assessment is described in more detail in Chapter 9 and effectively addresses sub-research question 2(a) (expression LoS of service road network). The performance resulting from this method formulates an answer to research question 2(c) (performance service road network).

The LoS boundaries, which are determined in the component-level modelling part within this research, are tested on the network level. This model generates more variability, and it is important that the LoS boundaries are robust enough to account for this variability. Substantial sensitivity can possibly limit the applicability of the LoS boundaries, which would diminish the validity of this research. This analysis addresses sub-research question 2(b) (applicability of LoS boundaries). The network-level modelling part of this research, along with answering the corresponding sub-research question, is able to effectively draw conclusion regarding research question 2 (upscaling of results to network-level model).

4

Service road system analysis

In this chapter, a high-level analysis is performed on airport service roads. Traffic engineering concepts vehicle heterogeneity (Section 4.1) and demand (Section 4.2) that are important to these environments are included in this chapter, as well as infrastructure design considerations (Section 4.3) and breakdown of service road networks into smaller infrastructure components (Section 4.4). This analysis ultimately formulates an answer to research question 1(a) (commonly present infrastructure components), but also explores other aspects relevant to traffic complications on service roads.

4.1. Traffic heterogeneity

One of the most important distinctions of airside service roads is its large variety of users compared to traditional roadway systems. Traditional roadways are usually dominated by private cars. Although some variety exist between different sizes of private vehicles, the largest group of users behave in a similar manner. Bigger vehicles such as recreational vehicles, trucks and buses typically consume roughly 10% of the traffic volume [57] on traditional roadway systems, whereas airside service road systems on the other hand are dominated by heavy traffic.

In Table 4.1, an overview of the large variety of vehicles present on Amsterdam Schiphol Airport [15] has been presented. From this, it can be concluded that the traffic is significantly more heterogeneous compared to traditional roadway systems, which complicates the analysis of traffic performance. Although the traffic composition of these vehicles may differ across different airports, many of these vehicle types are typically present at airports. The presence (or absence) of any vehicle type is usually due to operational differences.

Due to physical limitations, certain vehicles are unable to reach 30 km/h, which is typically the speed limit set on airport service roads. Other than travel speed, larger vehicles also have less acceleration, deceleration and manoeuvrability capabilities, therefore impeding faster moving vehicles. This is especially the case on 1x1 roads where overtaking is not allowed or possible. The size of the vehicle in itself also influences traffic performance.

Table 4.1: Service vehicle characteristics [15]

Type of Vehicle	Length (m)	Speed (km/h)	Type of Vehicle	Length (m)	Speed (km/h)
Baggage Trains	20	15	De-icer	10	15
Pallet Trains	20	15	Toilet/Water Service truck	8	30
Animal Transport	15	8	Cleaning van	5	30
High Loader	11	8	Motorised Stairs	8	15
Bus	13	30	Stairs	7	15
Fuel truck	8	25	Belt loader	7	15
Catering Truck	10	30	Mobile GPU	7	15
Assistance Vehicle	10	30	Personnel Truck	4	30
Fuel Dispenser	10	30	Mobile Office Truck	4	30
Push-back Truck	9	15	Mulach	4	15

4.2. Traffic demand

Compared to traditional roadway systems, the demand of service vehicle movements is less stochastic. Since the majority of the service vehicles are deployed to service an aircraft, which is called ground handling, the generation of these trips is highly dependent on the arrival and departure of this aircraft. Arrivals and departures of aircraft, as well as the underlying ground handling services, are planned with much accuracy, enabling efficient airport operations. Figure 4.1 presents a typical process chart on the ground handling services taking place during the turnaround phase of an aircraft. Each service-process requires the use of at least one service vehicle. Figure 4.2 presents a Gantt chart indicating the duration of each individual process for a Boeing 737-900. The duration of these processes and the number of vehicles required vary by aircraft type. Simplifications can be made and the aircraft can be divided into small, narrow-body and wide-body, as shown by research performed by De Jong on the service roads of Amsterdam Schiphol Airport [15].

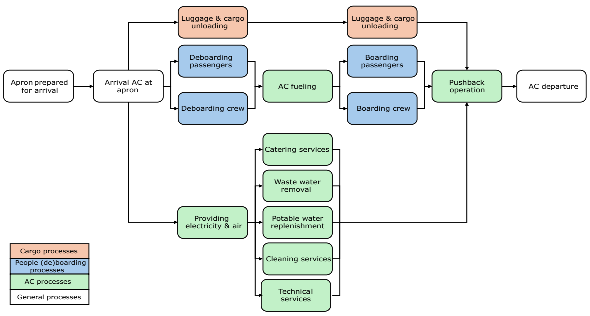


Figure 4.1: Typical aircraft ground handling process [19] [35]

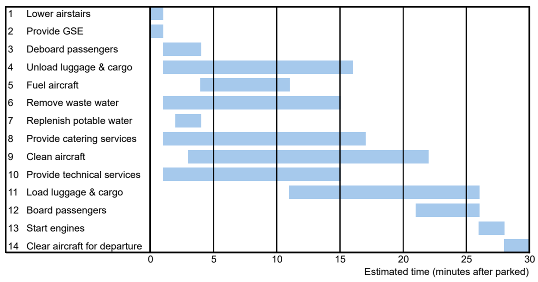


Figure 4.2: Gantt chart services of typical turnaround Boeing 737-900 [9]

4.3. Infrastructure design

The airside road traffic system consists of non-public roads that are used by different operational entities (which have been presented in 4.1) [15]. Separate infrastructure for these entities is required to organise vehicle movements, which enables a safe and efficient airside environment. Also, it reduces the possible conflicts with aircraft ground travel or taxiing, which is crucial for a timely arrival [31].

The design of a service road system is unique to each terminal, but key considerations are made when developing this type of network. Firstly, the network is dependent on the (combination of) terminal design concepts that is chosen for that particular airport. Variations exist, but Figure 4.3 presents the main concepts for terminal design known in the literature [50]. The “Standard” concept (in literature also referred to as “Linear”) is very common, but others have become more popular due to the increased spatial efficiency. For this reason, many larger airports have opted for “Pier” or “Satellite” configurations. “Concourses” configuration uses a large footprint, and a vast network of service roads is needed to facilitate the requirements for aircraft servicing. Lastly, mostly smaller airports opt for a “Shuttle” configuration, as this requires less capital investment needed for the terminal building. Larger airports (partly) using this concept also exist, and often deploy it when the fixed infrastructure of the terminal building is running at capacity. Having a “Shuttle” configuration increases the distance passengers and services have to cover, generally increasing the traffic demand on its roadway network.

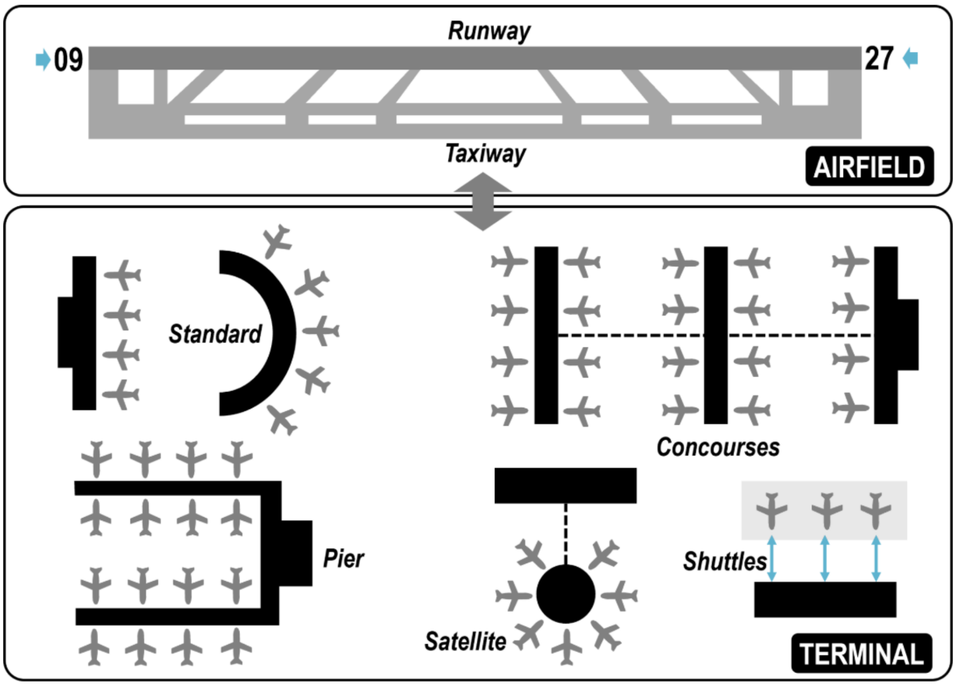


Figure 4.3: Terminal design concepts [50]

There are two main options for placing down main service roads: front-of-stand service roads, which are parallel and adjacent to the terminal, and back-of-stand service roads, which are situated behind the aircraft stands. Front-of-stand roads are preferred by IATA [30] due to their minimal conflict with aircraft movements. However, their development can be limited by nearby infrastructure, facilities and buildings. Back-of-stand roads on the other hand offer more flexibility and are often used in addition to front-of-stand roads when these have become insufficient to fulfil demand adequately.

The following findings are based on the analysis of “Airfield Vehicle Service Road Design and Operations” [49]. It has been concluded that infrastructure layout and design is relatively simple in general. Most airports use 1x1-lane roads, and only in some cases a decision has been made to add an extra lane, allowing slower vehicles to be overtaken by faster vehicles. Service road networks often contain basic intersections and T-junctions, but roundabouts are also implemented more frequently in the recent past. Airport service roads generally require wider lanes to accommodate the larger size of vehicles. The turning-radius of such vehicles have been accounted for while developing such networks. Intersection control is mostly done via yield signs and road markings, often giving priority to through traffic on the main road. Some airports also choose to implement stop-signs to improve safety. Since back-of-stand service roads can cross aircraft taxiways, it is undesirable to have a queue near the crossing of a taxiway. Many service road designs therefore give priority to movements coming from a taxiway. Service road vehicles always give priority to aircraft movements, either operating on its own or being pushed back by a tractor, because these are more time-sensitive and it enhances general safety. The use of traffic lights is very uncommon. Speed limits varies across airports, but is typically around 30 km/h. While ICAO has not established specific international regulations, local guidelines typically serve as a basis for traffic laws and rules at airports [15]. This also determines which side of the road is being used (left or right) and which traffic signs and road pavements are implemented.

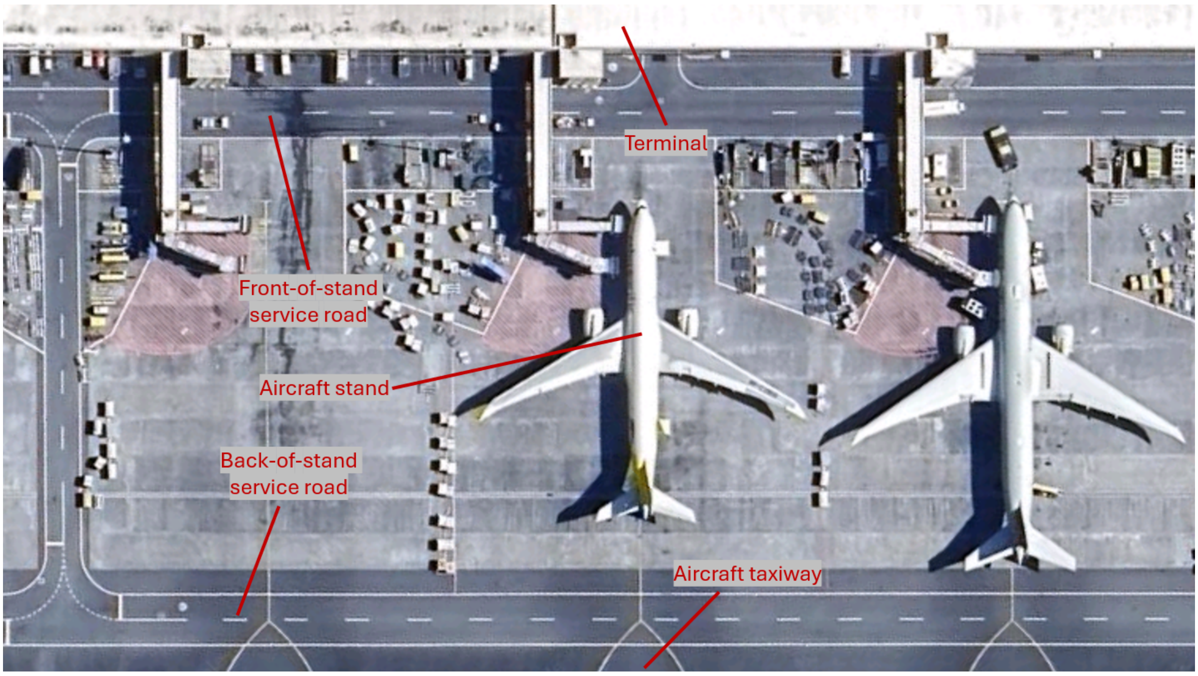


Figure 4.4: Service road example of Ninoy Aquino International Airport [22]

4.4. Infrastructure breakdown

This analysis will dive into the different components that are often present in airside service road systems and constitute the basis of the service road infrastructure. This is crucial for the modelling phase later in this research (Chapter 5), as this will determine which pieces of infrastructure will be included. It will therefore also formulate an answer to research question 1a.

Various large-sized airports (20+ million passengers per year) are considered and inspected using Google Earth Pro [21], including Schiphol Amsterdam, Frankfurt, London Heathrow, Incheon Seoul, Beijing Capital, Kempegowda Bangalore, Chicago O'Hare and Montreal-Pierre Elliott Trudeau. For each individual infrastructure component an example is given from one of the mentioned airports.

While analysing the layouts of these airports, it is again noted that airports use relatively simple infrastructure design. In the analysed cases, most roads consist of one lane in each direction. Two-lane roads are present on more modern airports, as is the case with Incheon, which is a result of the capacity-related concerns for future demand. For this reason, two-lane infrastructure components are however not included in this research, since this study primarily focuses on capacity-constrained infrastructure. The use of signalised intersections is not observed. Roundabouts are utilised at critical infrastructure bottlenecks, but their implementation is often constrained by the limited space available near terminal buildings. Another commonly used infrastructure component is an uncontrolled intersection, where vehicles need to give priority to vehicles approaching from the right (in case of right-hand traffic). However, these are generally implemented in low-demand areas of the network. Therefore, they are also excluded from this research.

The most important components from this analysis are presented in Figure 4.5. The key infrastructure components that will be analysed contain four-way priority intersection (4.5a), four-way roundabouts (4.5b), thee-way priority intersection (4.5c), three-way alternative intersection (4.5d) and a main road segment connected to aircraft aprons (4.5e). Four-way priority intersections consist of a prioritised road and a side road, which is controlled using priority signs to give way to vehicles on the main road. Four-way roundabouts follow traditional traffic rules, giving priority to vehicles on the circular road. It therefore does not prioritise movements from any particular direction. Three-way priority intersections are implemented similarly as four-way intersections, and are often used for connections between front-of-stand and back-of-stand main roads. For this reason, they are included in this research as well. An alternative design for three-way intersection is commonly present at airports. Within this research, this design is labelled as a “three-way alternative intersection”. These have a uncommon way of giving priority. In the example given in Figure 4.5d, traffic coming from the east and west direction need to give priority to traffic from the north direction. This is designed in this way, because vehicles travelling on this link intersect with main taxiways (as can be seen in the top of Figure 4.5d) and moving aircraft may not be impeded by service vehicles. Lastly, another infrastructure component unique to service roads are main road segments that are connected to the aprons. These can either be front-of-stand and back-of-stand roads. The reason that these are included in this research as a segment rather than a singular three-way intersection, is because the accumulation of these intersections has a substantial influence on the overall performance and delay of traffic. Additionally, the intersections on a main road segment are positioned in close proximity of each other, further impacting traffic performance as spill-backs can have a significant influence on upstream aircraft aprons. Within the limited time frame of this research, simplifications have to made as to how to analyse main roads. It has been decided to create a model for a main road with three aircraft stands. This can effectively analyse the results that are impacted by the accumulation of multiple aircraft stands. Otherwise, having the number of aircraft stands included as an additional variable in the model would complicate the design of this research, resulting in excessive modelling efforts.

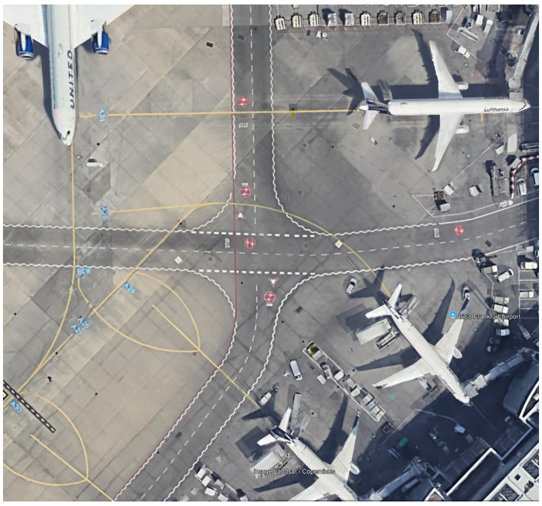
4.5. Chapter conclusion: commonly present infrastructure components

This section formulates an answer to research question 1(a) specifically, which explores the infrastructure components frequently present at airports that are included in the modelling phase of this research.

Based on the analysis presented in this chapter, several key infrastructure components commonly found in airside service road systems need to be modelled and analysed. These components include four-way priority intersections, four-way roundabouts, three-way priority intersections, three-way alternative intersections, and main road segments connected to aprons.

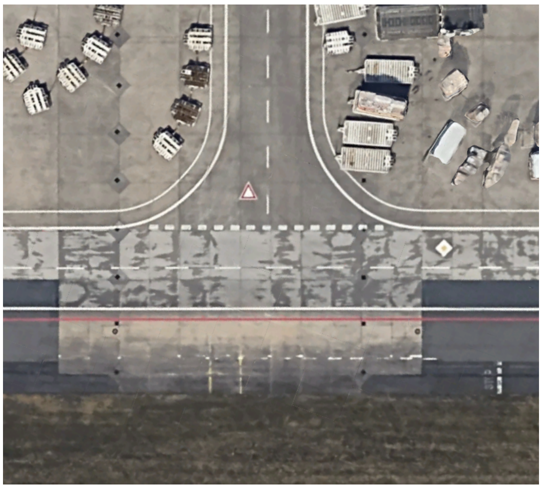
Four-way priority intersections are characterised by a prioritised road and a side road, controlled by priority signs to give way to vehicles on the main road. Four-way roundabouts follow traditional traffic rules, giving priority to vehicles on the circular road without prioritising movements from any particular direction. Three-way priority intersections are similar to four-way intersections and are often used for connections between front-of-stand and back-of-stand main roads. Three-way alternative intersections have a unique way of giving priority, designed to ensure that service vehicles do not impede moving aircraft. Main road segments connected to aprons are included as a segment rather than a singular intersection due to their substantial influence on the overall performance and delay of through-going traffic.

These components are crucial for understanding the efficiency of airside service road systems, as they represent the primary elements that facilitate traffic flow and vehicle interactions in airport environments. It is important to note that variations of these components exist, but a framework is designed to evaluate the basic infrastructure, after which this can be replicated on other possible configurations as well. Additionally, as these components are one-lane configurations, they are susceptible to congestion.

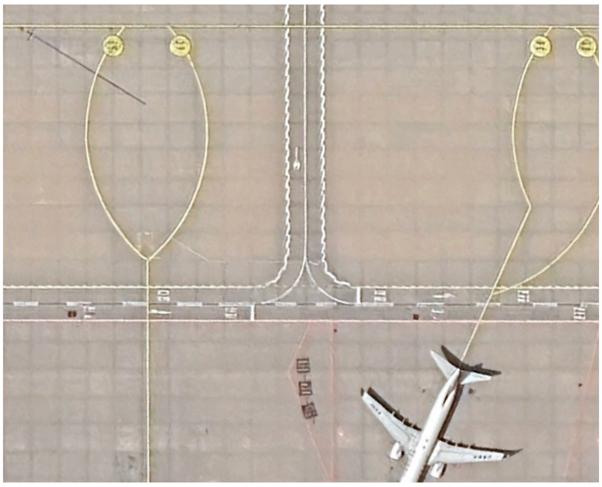


(a) Four-way priority intersection, Frankfurt Airport

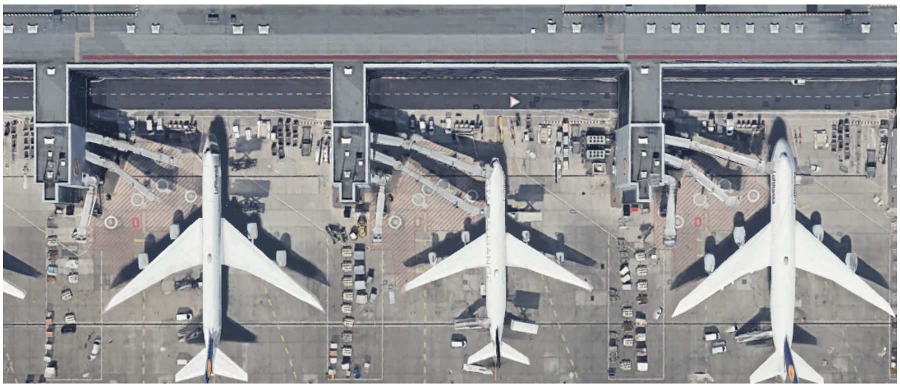
(b) Four-way roundabout intersection, London Heathrow



(c) Three-way priority intersection, Frankfurt Airport



(d) Three-way alternative intersection, Incheon Seoul



(e) Main road segment connected to aprons, Frankfurt Airport

Figure 4.5: Basic service road infrastructure components [21]

5

VISSIM model input

This chapter reports the VISSIM model input used within this research. First, the traffic composition of airport service roads is estimated in Section 5.1. Hereafter, other traffic-related parameters - including vehicle behaviour, physical characteristics and routing-logic - are discussed in Section 5.2. Additionally, the VISSIM simulation and evaluation settings are presented in this section. This chapter does not address a specific research question on its own, but it provides a foundation for further analyses in this study.

5.1. Vehicle composition estimation

An important aspect of the traffic model is the vehicle composition, also called traffic mix. Since airport service roads have a large variety of different users with diverse characteristics (as was shown in Service road system analysis in Section 4.1), this will ultimately impact traffic performance [14]. To make a valid interpretation of these models, it is important to create a solid reference point that accurately represents the traffic composition of a typical airport system. The HCM [58] also states that setting up a reference is crucial for analysis of the performance of roadway infrastructure, because it allows to analyse results with alternative conditions better by comparing them with the reference. The reference traffic composition is hereafter referred to as the “Base case”.

It is important to notice that the service vehicle traffic composition varies between airports, as it is dependent on various factors. By analysing these factors, an estimation can be made for the average or typical traffic composition. Two key elements are predominantly influential on the amount of vehicles of each type that are present on an airport: aircraft composition and the stand type composition of the airport. The “base case” traffic composition resulting from this analysis is presented in Figure 5.3.

5.1.1. Aircraft composition

One primary factor that determines the vehicle composition of the airside service roads is the aircraft composition. In most aircraft models, a manual for airport planning indicates which service vehicles are required for that particular aircraft and how many [3, 9, 10]. For uniformity reasons, most aircraft can be serviced using the same type of vehicles, but the number required is primarily dependent on the size of the aircraft. Larger aircraft can for example bring more passengers that bring more luggage, requiring additional baggage service vehicles. Large aircraft also hold more space for cargo. Because of the size of the aircraft, additional material is needed to load and unload, while the number of service vehicles of another type may stay the same. Having a relatively vast amount of large aircraft in the airport mix, as is the case with most global hub-and-spoke airports, will therefore have a different traffic composition than more regional point-to-point airports with smaller aircraft.

As there are many different aircraft types with different sizes and needs, a simplification will be made by grouping the types into two groups: narrow and wide body aircraft. According to the ICAO reference code, these are aircraft code C (narrow body) and D, E and F (wide body). The presence of ICAO code A and B at large commercial airports are neglectable, and are therefore disregarded within this research.

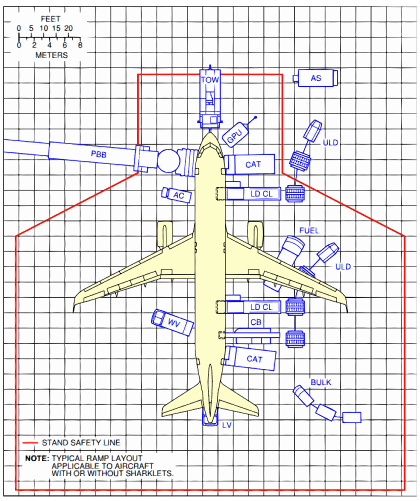
Research on the service roads of Amsterdam Schiphol Airport [15] has noticed that the aircraft types within these two segments (narrow and wide body) share the amount of service vehicles required to a great extent, which makes the issue less computational and analytically complex.

Cargo aircraft are not being considered during further analyses. These type of aircraft require unique operations compared to passenger air travel, but it has been decided to not include this as a factor for determining the “base case” traffic estimation. Reason for that is threefold. Firstly, despite its unique operations, the types of vehicles needed to serve these aircraft are roughly the same [11]. Additionally, at many airports these operations are physically separated from the passenger operations, as often a cargo terminal is build at a different location (for example, on the other side of the airport premises). Lastly, at most large airports only a small portion of the flights are performed by dedicated freight-only aircraft, not considering cargo-centric airports. These type of airports are more rare and separate research should be conducted if it is deemed of relevance by the aviation industry.

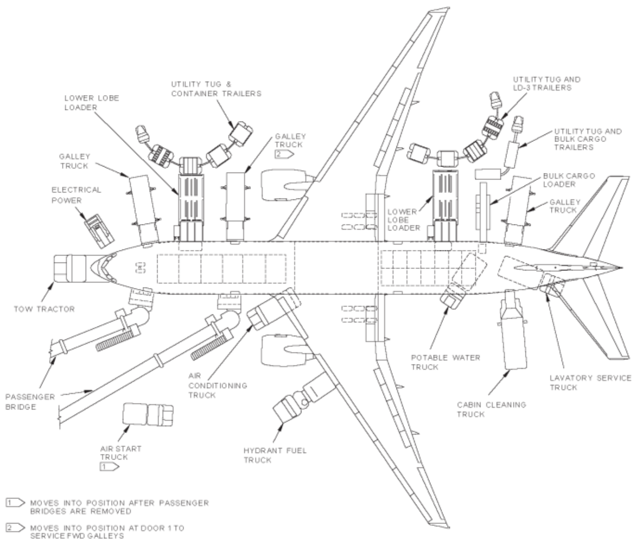
5.1.2. Stand type composition

Within airport design, two types of aircraft stands (also called aprons) can be distinguished: contact and remote. Contact stands are within walkable distance of the terminal building, and aircraft are either directly connected using passenger boarding (jet) bridges (as seen in Figures 5.1a and 5.1b), or passengers have to walk a short distance and enplane using remote stairs [37]. Remote stands are located further away and need a transportation mode to connect people from the terminal building to the aircraft [38], and passengers are boarded using remote stairs in any case.

Both types of stands are usually present at larger airports. Generally the use of contact stands are preferred to increase passenger comfort and decrease operational costs, while remote stands are often deployed during busy hours to cover peak demand. Having remote stands reduces the size required for a terminal building and therefore reduce capital investment when developing an airport. At large airports, they are generally deployed on top of the contact stands to increase capacity during peak hours.



(a) Boeing 777 [11]



(b) Airbus A320 [3]

Figure 5.1: Typical servicing layout narrow-body (a) and wide-body (b)

Remote stand people transport

Passenger and crew transport is needed when an aircraft is parked at a remote stand, which is primarily why stand type composition influences the service vehicle traffic composition. Passengers and crew are usually transported by bus, which are often specially modified for airports to accommodate as many passengers as possible for short distances. Capacity of these vehicles can differ, but are typically between around 80 to 140 [55]. Within this research, a bus capacity of 100 will be used for the determination of the amount of buses needed per aircraft type.

Capacity of wide-body aircraft vary significantly, and can be anything between 200 and 850 passengers, while capacity of narrow-body aircraft is up to roughly 250 passengers [5]. To determine the buses required for both aircraft sizes, it is important to know (on average) how many actual passengers are being transported by each type. Suggestions are made in literature regarding load factors, but none made distinctions between narrow and wide body aircraft. Therefore, data analysis of an undisclosed hub-airport is performed. The airport in question is a large hub-airport, transporting 25-30 million annual passengers per year, situated in North-America. From the flight data of an entire month, the aircraft size characterised by ICAO coding and number of passengers transported are recorded. The data analysis has revealed the Box and Whisker plots shown underneath (figures 5.2a and 5.2b). It shows that the third quartile of narrow- and wide-body aircraft are 174 and 332 passengers respectively. Considering a capacity of 100 passengers per bus, this means that two buses are needed to feed narrow-body aircraft on remote stands, while wide-body aircraft need four. These number of buses are assumed for further analyses.

(a) Narrow-body

(b) Wide-body

Figure 5.2: Box and Whisker plots of number of passengers transported by narrow-body (a) and wide-body (b) aircraft

The analysis discussed has, along with findings from the Amsterdam Schiphol Airport study [15], resulted in the summarised Table 5.1. This table indicates how many service vehicles is needed of each type to service these vehicles, split between contact and remote stand (stand type composition), and narrow- versus wide-body (aircraft composition).

The number of vehicle types have been reduced compared to Table 4.1 that has been presented before, which introduced a first draft of service vehicles that can be present at airports. Several vehicle types have been excluded from further analysis for two reasons. Firstly, vehicles excluded are very dependent on the airport design, and are therefore not present on every airport service road system. Secondly, some vehicles such as motorised stairs and de-icer vehicles do not travel around the entire system, but are typically stationed nearby the aircraft stands to service them.

From Table 5.1, it becomes clear that aircraft and stand composition have a moderate impact on the traffic composition. Wide-body aircraft in general need more service vehicles than narrow-body, while remote stands require additional vehicles (buses) for people transport.

Table 5.1: Service vehicles required per aircraft and stand type [3, 11, 15]

Type of aircraft servicing → Type of vehicle ↓	Contact Wide-body	Contact Narrow-body	Remote Wide-body	Remote Narrow-body
Bus	-	-	4	2
Catering truck	3	2	3	2
Fuel truck	1	1	1	1
Cleaning van	1	1	1	1
Toilet/water service truck	2	2	2	2
Baggage trains	2 (5 dolly's)	2 (5 dolly's)	2 (5 dolly's)	2 (5 dolly's)
Cargo trains	2 (6 dolly's)	-	2 (6 dolly's)	-
Push-back tractor	1	1	1	1
Belt loader	2	1	2	1
High loader	1	-	1	-

Based on Table 5.1, an estimation for the "base case" traffic composition will be made. Apart from this data, there are two input parameters that determine this traffic composition: penetration rate for wide-body aircraft and penetration rate for contact stands. The penetration rate for wide-body aircraft determines the penetration rate for narrow-body aircraft, which is $1 - P_{wb}$. Similarly, the penetration rate for remote stands is dependent on the penetration rate for contact stands, which is $1 - P_{cs}$. The following mathematical formulation calculates the proportions for each vehicle type:

$$S_{i,j} = \begin{pmatrix} P_{wb} \times P_{cs} \\ (1 - P_{wb}) \times P_{cs} \\ P_{wb} \times (1 - P_{cs}) \\ (1 - P_{wb}) \times (1 - P_{cs}) \end{pmatrix} \times I_i \tag{5.1}$$

where:

$S_{i,j}$: Share of vehicle type i originating from type of aircraft servicing j

P_{wb} : Penetration rate for wide-body aircraft

P_{cs} : Penetration rate for contact stands

I_i : Input Table 5.1 number of service vehicles of type i required for aircraft servicing

The resulting relative share for vehicle type i in the "base case" is then calculated by the following formula. This effectively sums the share for any vehicle type i over all columns j of Table 5.1, which includes the vehicle types requirements for each servicing type.

$$S_i = \sum_j S_{i,j} \tag{5.2}$$

The penetration rate for wide-body aircraft P_{wb} has been determined by analysing airport flight data from three different undisclosed airports. These three undisclosed airports are described as follows: large-sized airports with 25+ million annual passengers, two of them are hub-airports situated in Asia and North-America, while the third airport serves a point-to-point network in Europe. The ratios between wide and narrow-body aircraft vary significantly across airports, which makes it hard to create a solid estimation for the "base case" scenario. The share of wide-body aircraft are 12.16%, 16.12% and 39.05% for the three airports.

The reason that these ratios vary is that each airport serves different markets and have different flight networks. Point-to-point networks generally serve more narrow-body aircraft, while global hubs in general serve more wide-body aircraft. Larger airports are more important to this research as they are more subjected to capacity issues. While wide-body aircraft are more frequently seen at larger airports, narrow-body flights still account for the majority of flights. Therefore, the penetration rate P_{wb} has been set at 25%. To estimate a representative penetration rate for contact stands P_{cs} is even more dependent on external factors, which is mostly related to airport design. In most global airports, passengers are served through contact stands. However, there are also examples where a significant portion of the passengers are transported using buses, such as Dubai International Airport. For later analyses, it is important to include buses. Therefore, the penetration rate for contact stands P_{cs} is set at 75%.

With the aforementioned input and mathematical formulation, the resulting vehicle composition of the "base case" is presented in Figure 5.3. It is important to notice that this is used a reference point that tries to obtain more solid estimations for later analyses. As discussed in this paragraph, vehicle composition may vary substantially from airport to airport. For the purpose of this research however, which is to get better understanding in the capacity of service roads for all airports rather than one in particular, this "base case" vehicle composition will serve as a solid foundation.

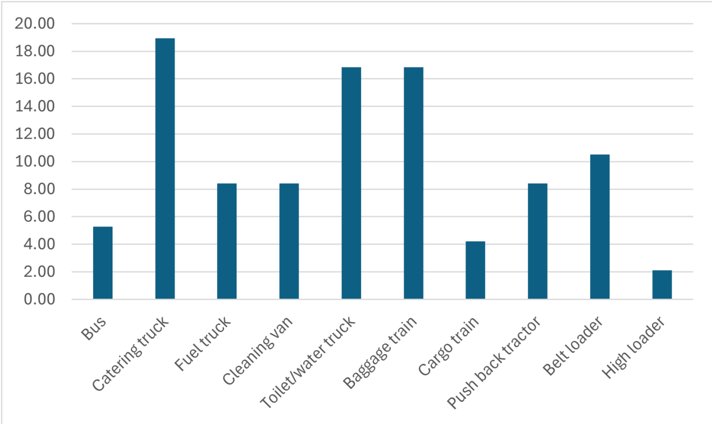


Figure 5.3: Vehicle composition estimation of "base case" scenario, share per vehicle type

5.2. Input parameters

This section describes all relevant input parameters for the VISSIM models that is used for further analyses. If not addressed separately, the VISSIM model input holds true for both the component-level models as the network-level models. Visualisations of the design of the VISSIM component-level models are presented in Appendix A.1.

5.2.1. Vehicle input

This paragraph focuses on the vehicle input parameters that have been used in the VISSIM-models. 3D-models of each vehicle type has been downloaded from 3D Warehouse [1] to accurately represent the correct dimensions of such vehicles. These models are scaled to match the length and width of the vehicles that have been reported by the Amsterdam Schiphol Airport study [15] and input numbers that are used by aviation industry companies. From these sources, the speed profiles are also derived and implemented as input, which will be elaborated underneath. Table 5.2 summarises the vehicle parameters. Other than the ten vehicle types that have been included from Table 5.1, also passenger cars have been included and characterised. This is important for determining the relevant impact of each vehicle type compared to traditional passenger cars, which will be explained in Chapter 6.1 (Passenger Car Unit analysis).

Speed profiles

Each vehicle type within all models are assigned a speed profile. These profiles determine the speed that vehicles traverse across the infrastructure. There are three different speed profiles within the model: Service 30, 25 and 15. The number of these profiles effectively represents the maximum speed that a vehicle is allowed or limited to. The speeds are stochastically distributed to accurately represent small variations that in reality also occur. Therefore, Service 30 has a distribution between 27 en 33 km/h, Service 25 between 22 and 28 km/h, and Service 15 between 13 and 17 km/h, all uniformly distributed.

Table 5.2: Vehicle input parameters VISSIM-model

Type of Vehicle	Length (m)	Width (m)	Speed profile	Acceleration/deceleration profile
Passenger car	4.5	2.0	Service 30	Car (default VISSIM)
Airport bus	13.0	3.5	Service 30	Airport heavy vehicle
Catering truck	10.0	3.0	Service 30	Airport heavy vehicle
Fuel truck	12.0	2.5	Service 25	Airport heavy vehicle
Cleaning van	5.0	2.0	Service 30	Airport light vehicle
Toilet/water truck	8.0	3.0	Service 30	Airport heavy vehicle
Baggage train	20.5	1.5	Service 15	Airport train
Cargo train	20.5	1.5	Service 15	Airport train
Push-back tractor	8.0	3.0	Service 15	Airport heavy vehicle
Belt loader	7.0	2.5	Service 15	Airport heavy vehicle
High loader	11.0	2.0	Service 15	Airport heavy vehicle

The second part of the speed profiles is the speeds of the vehicles while turning on intersections. Turning speeds at roundabouts have been differentiated from other intersection types. Turning speeds for non-roundabout intersections have been divided into left-turning and right-turning speeds. Speed analysis of turning vehicles performed by Wolfermann et al. [62] reveals a difference between right and left turning actions, which is primarily explained by the difference in turning radius. With right-hand traffic (as is the case within this research), right-turning vehicles therefore have a lower average speed than left-turning vehicles. To visualise the difference between the left and right turn speed profiles, a test run is performed. The speed of three different vehicle types are tracked in free-flow state and presented in Figure 5.4. From each profile service 30, 25 and 15, one vehicle type belonging to that profile is tracked.

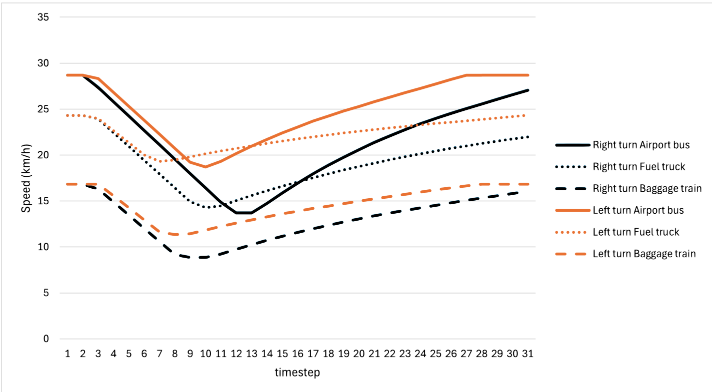


Figure 5.4: Speed profiles left and right turning vehicles

Roundabout speed profiles have been derived using roundabout speed analysis for different entrance speeds and roundabout radii [44]. As profile “Service 25” is only used by fuel trucks, which is considered a large vehicle with poor manoeuvrability, it has been decided that it has the same turning and roundabout speed profile as “Service 15”.

The max speed ranges have been implemented in VISSIM by setting the link speeds according to Table 5.3. Turning and roundabout speeds have been implemented using VISSIM’s Reduced Speed Area function. The target speed is set accordingly, and vehicles brake before the designated area to obtain the reduced speed for that particular turn. From Figure 5.4 it can be concluded that the speed profiles behave as intended, as vehicles start with the expected speed that is inside the max speed range, after which they will decelerate to the required left or right-turn speed range. After the vehicles have passed the reduced speed area, they will accelerate again.

Acceleration and deceleration profiles

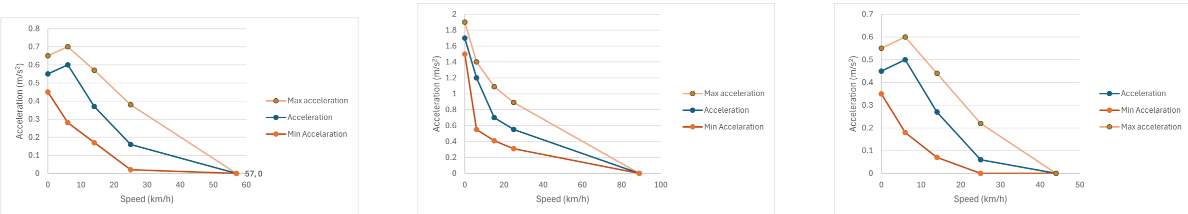
Each vehicle type is assigned an acceleration and deceleration profile. As these profiles are largely influenced by the vehicles size and power, three different profiles have been created. These are Airport

Table 5.3: Speed profiles (uniformly distributed)

Profile	Max range (km/h)	L-turn range (km/h)	R-turn range (km/h)	Roundabout range (km/h)
Service 30	27 - 33	17 - 23	12 - 18	19 - 23
Service 25	22 - 28	8.5 - 11.5	6 - 9	10 - 12
Service 15	13 - 17	8.5 - 11.5	6 - 9	10 - 12

heavy vehicle, Airport light vehicle and Airport train. Also passenger cars are included in this research for later analysis, but default values determined by VISSIM are used for these vehicles.

Numerous studies have focussed on acceleration profiles of different vehicle types. Many research has been invested in speeds of around 50 km/h, which is particularly useful for capacity-constrained urban roads. However, Bokare & Maurya [12] have also tracked speed-acceleration functions for slower moving speed ranges (20-30 km/h). Therefore, findings of this study will be implemented in VISSIM. In VISSIM, this input is called desired acceleration, and all vehicles are assigned a value randomly based on the desired acceleration function. Figure 5.5 shows the acceleration-speed functions of the three different acceleration profiles. Airport light vehicle is based on a petrol car from the research of Bokare & Maurya [12], while airport heavy vehicle and airport train have been based on trucks. Airport heavy vehicle and airport train have identically shaped functions, but the values for trains have been decreased slightly for more accurate representation of its behaviour. Airport trains (baggage and cargo trains) are unique vehicles that do not occur on public roads. Because they are long and heavy and have five or six trailers, it has been decided to alter the distribution in this way.



(a) Airport heavy vehicle **(b)** Airport light vehicle **(c)** Airport train

Figure 5.5: Acceleration functions [12]

VISSIM uses constant desired deceleration values of vehicles by default. A distinction of deceleration values is again made between airport light, heavy and train vehicles. Input values have again been derived from the research of Bokare & Maurya [12] for speeds specifically between 20-30 km/h. Light vehicles have been assigned a desired deceleration between -4.30 m/s^2 and -2.08 m/s^2. Heavy vehicles decelerate substantially slower, and are assigned a desired deceleration range of -0.47 and -0.22 m/s^2. Desired deceleration rates of airport trains are again, for the same reason its acceleration is also lower, and decelerates between -0.37 and -0.12 m/s^2.

5.2.2. Traffic distribution

As traffic volume varies depending on the type of analysis, a traffic distribution is kept constant to effectively evaluate the performance of each infrastructure component. The four-way priority, four-way roundabout, three-way priority and three-way alternative intersections are modelled with a main traffic stream from East to West (and vice versa) and a minor traffic stream from North to South (and vice versa). Traffic coming from the main traffic stream is three times as dense as traffic from the minor traffic stream. This is purposefully done to represent main roads and side roads present on airport service roads.

For main road segments, the traffic stream coming from the aircraft stands are 5% of the traffic stream from the main road section. Each individual aircraft stand therefore has a small contribution to the main traffic stream, which accumulates to a significant portion if the number of aircraft stands is increased.

5.2.3. Car-following model

Two types of car-following (CF) models are integrated into Vissim, which are CF-theories developed by Rainer Wiedemann, and are widely used for the purpose of microscopic traffic simulation. The models are called Wiedemann 74 (W-74) and Wiedemann 99 (W-99) and are formulated in 1974 and 1999, respectively. The W-74 CF model is an earlier version that uses a simpler set of thresholds and equations to calculate acceleration [60]. The W-99 CF model is a more refined version that incorporates additional thresholds and more complex equations to better capture realistic driving behaviour, such as oscillatory behaviour and anticipation of the leading vehicle's actions. A calibration model developed for VISSIM specifically [61] as well as the VISSIM manual itself have indicated that W-74 is sufficient for urban roads and arterials, but research on traffic simulation with heterogenous traffic conditions in India [48] has found that both W-74 and W-99 behave similarly.

Comparing both Wiedemann CF-theories on the airside infrastructure created in VISSIM has identified an issue with the use of W-74 and slow-moving traffic. A leading vehicle constantly increases and decreases its speed of approximately plus or minus 3 km/h. This fluctuation has a relatively small effect on vehicles travelling faster than 30 km/h, but is very profound on vehicles travelling only 15 km/h. The following vehicles react to this fluctuation, and as many platoons are formed in the models because of the traffic heterogeneity, this phenomenon will have an unrealistic impact on the general traffic flow. These fluctuations of the leading vehicle does not occur within the W-99 CF model. It has therefore been decided that W-99 is more appropriate for this research.

5.2.4. Route assignment

Within VISSIM, one can choose between static and dynamic route assignment. Static route assignment in VISSIM involves predefined routes for vehicles, which ensures consistent traffic patterns and simplifies analysis. It is ideal for predictable traffic flows and reduces computational complexity. Dynamic route assignment, on the other hand, allows vehicles to choose routes based on real-time traffic conditions, adapting to congestion and incidents. This approach provides a more realistic simulation of traffic behaviour and can improve overall network performance by optimising route choices dynamically. [45]

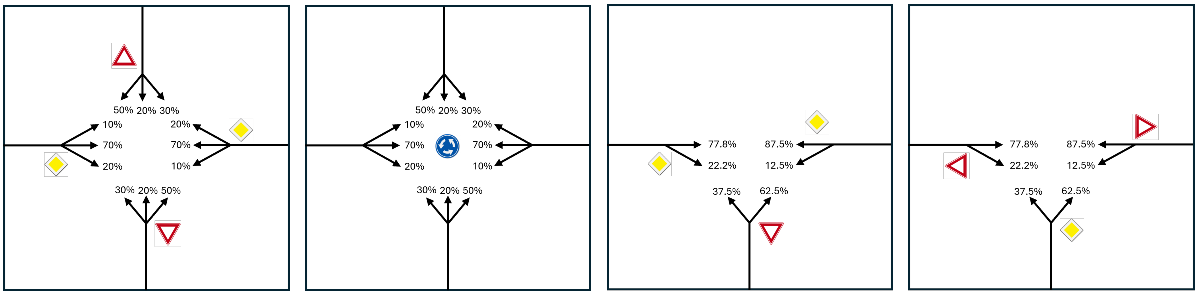
Static route assignment helps in analysing traffic flow at unsignalised intersections. When comparing different infrastructure components, as is the case in this study, it is important to keep as many factors constant as much as possible. Therefore, static route assignment is used for this part of the research. This also remains true for network-analysis in Chapter 9. Using this routing logic will result in fixed turning rates for each direction.

Since this simulation-model is not based on real-life airport traffic data, it is important to model traffic flows in a representative manner so that useful conclusions can be drawn regarding the performance of such intersections. Consequently, representative turning rates for typical intersections need to be found. Similar research done by Kollar [34], which analysed the relative impact of different vehicles on roundabouts, three-way and four-way intersections, has used turning rates that are graphically represented in Figure 5.6. These turning rates will be used for all component-level VISSIM-models in this research. It is important to notice that this is a stochastic process, and vehicles are assigned a route based on the corresponding probabilities once it has passed the vehicle route choice line.

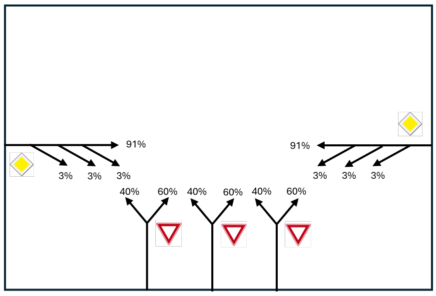
Three-way intersections are missing one direction compared to four-way intersections, and this share is distributed across the remaining directions according to the relative share. In this way, the proportions between each direction stays the same compared to four-way intersections. The main road segment has a turning rate of 3% towards any aircraft stand. This has been chosen to accurately represent a main road segment, as only a small portion of traffic makes a turn at any random aircraft stand. Having one aircraft serviced at a stand per hour, which is an approximation during peak airport conditions, only 10 to 19 service vehicles (according to Table 5.1, service vehicle requirements per aircraft and stand type) will have that particular stand as its destination.

5.2.5. Simulation and evaluation settings

Each run is simulated with a data-collection period of 3600 seconds (1 hour). A warm-up period of 3 minutes is installed, so that vehicles have time to occupy the model to a stable and representative level. Three minutes is sufficient, as the component-level models are relatively small, and even the slowest



(a) 4-way priority intersection **(b)** 4-way roundabout intersection **(c)** 3-way priority intersection **(d)** 3-way alternative intersection



(e) Main road segment

Figure 5.6: Turning rates of component-level base models

vehicle takes only about 65 seconds to enter and exit the model. These settings ensure that every simulation run includes a one-hour data collection period that is fully representative. Each scenario (scenario-specific input will be discussed in each separate analysis) will be simulated 10 times to obtain reliable and accurate results. This is because vehicles are generated and distributed (route-choice) stochastically, meaning that each scenario results in unique results.

For each simulation, the number of vehicles of each type is recorded using VISSIM's data-collection points. These record data for each origin-destination combination possible. For example, a four-way intersection results into 12 different origin-destination combinations (3 turning movements per direction North, East, South and West). For every origin-destination combination, the number of vehicles of all 11 vehicle types is recorded. Additionally, the average travel time for each origin-destination combination and vehicle type is recorded. The travel time for a specific origin-destination combination is only recorded when any vehicle crosses both the entry and exit point of the data-measurement area, which are defined by the data-collection points in VISSIM. For each model, the travel time is measured for a segment of 270 meters, which is considered the area including the approach (upstream) and departure road (downstream) of the intersection.

The results are then transformed into a total delay for that specific run using data-transformation in Microsoft Excel. The delay per vehicle type is calculated by multiplying the average travel time for a specific vehicle type and origin-destination combination with the number of vehicles recorded for the corresponding entry point. This results in a so-called delay matrix. Summing all values in the delay matrix of one particular run results into a total delay for that specific run. Combining this with the number of vehicles of each vehicle type results into the required output needed for later analyses. An example of the results of three runs have been presented in Table 5.4 to illustrate what the results of each simulation looks like after data transformation.

Table 5.4: Delay transformation results example

Run	Delay	Vehicle type 1	Vehicle type 2	Vehicle type 3	...
1	4206.22	50	18	75	...
2	3316.14	54	15	58	...
3	3795.91	50	20	68	...

6

Passenger Car Unit of airport service vehicles

This chapter focuses on calculating the PCU values for airport service vehicles to accurately capture the traffic heterogeneity present in these environments. It first describes the methodology used to find accurate PCUs in Section 6.1, including setting up the VISSIM models and outlining the expected results. Then, the results of the analysis are reported and interpreted in Section 6.2. Lastly, a chapter conclusion is written (Section 6.3), which is specifically addressing research question 1(a). This question is interested in finding the PCU values for airside service road vehicles.

6.1. Analysis approach

The heterogeneous nature of the service roads has a significant impact on the capacity of the infrastructure [14]. In the literature Passenger Car Unit (PCU), also referred to as Passenger Car Equivalent, is often used to compare the impact of different vehicle types on traffic performance indicators such as delays, travel time or travel speed [58]. PCU will therefore be used as a measurement for capturing the heterogeneous traffic mix into a standardised unit within this research. It compares the influence of a certain vehicle type with the influence of a typical passenger car, which has a reference PCU value of 1.

Literature has found that speed, size, acceleration capability and manoeuvrability are important indicators for the PCU estimation [16]. Due to the variation in speed, size, acceleration capability, and manoeuvrability among service road users that are included in this study, it is anticipated that different vehicle types will significantly impact infrastructure performance and limit the capacity in terms of vehicles per hour. The mentioned traffic behaviour factors can be incorporated and represented within the VISSIM traffic simulation model.

Research by Sugiarto et al. [53] has concluded that Multiple Linear Regression (MLR) is effective, efficient and appropriate for estimating PCU values under heterogenous traffic conditions. This research has performed this analysis for Indonesian city Banda Aceh, from which its roads are subjected to a large variety of vehicle users: motorcycles, passenger cars, motorised rickshaws and different sized trucks and buses. Despite its value for determining PCU's under these conditions, the degree of heterogeneity on airport service roads is even more intense. Therefore, it would be of interest to evaluate whether this methodology can effectively address this high degree of heterogeneity as well. Comparative studies of PCU estimation methods by Mondal et al. [43] and Raj et al. [47] have also acknowledged that MLR is one of the most useful techniques for determining PCU values on intersections. The literature review (Chapter 2) indicates that MLR is particularly adept at managing traffic heterogeneity, which is a common characteristic of service roads [43, 47]. It has therefore been decided to use MLR for determining PCU values within this research as well, using statistical analysis package SPSS. The combination of traffic simulation and statistical analysis is able to predict PCU values of traffic systems, and provides valuable insights for traffic management. VISSIM is capable of imitating roadway infrastructure based on speed, size, acceleration capability and manoeuvrability accurately, while SPSS can analyse the data from the VISSIM model and test the linear relationship between the dependent variable and independent variables.

Various implementations of MLR applied to roadway systems to obtain PCU values exist in the literature. Research analysed [43] [47] [53] use the number of vehicles of each vehicle type i as independent variables for the MLR model. An advantage of this method is that it is able to compare the regression coefficients of each vehicle type directly with each other. The choice of the dependent variable varies and is mostly dependent on the focus of the study. Highway applications are often modelled using Free Flow Speed, while with urban environments and intersections it is more useful to calculate the experienced delay, as indicated by the Highway Capacity Manual [58]. PCU estimations based on delay by Raj et al. [47] presents the possibility of computing the delay experienced by one driver as the difference between the delay of a vehicle i and the “base” delay, which is considered the delay of the reference vehicle (passenger car). An additional advantage of choosing delay as the dependent variable in this research is the importance of this indicator for the determination of LoS later in this research (Section 8.1).

Delay can be calculated using travel time: actual travel time of vehicle i minus the optimal travel time. This is more convenient for this research, since VISSIM is only able to measure travel time between specific data measurement points and not the delay. The total delay is hereafter calculated using the method described in Section 5.2.5 (Simulation and evaluation settings), which leads to a total delay (delay of all vehicles summed up) for each run. Since this research has three different speed profiles that differ substantially, it would be unrepresentative to calculate the delay by comparing to one reference point only. For example, if the speed profile of 30 km/h is chosen as the reference, there would always be delay of a vehicle that can only travel 15 km/h, while in practice this is not true. Therefore, there are three different reference points created: 30, 25 and 15 km/h. Each vehicle type is compared to a reference point that corresponds to its speed profile (see Table 5.2 for the speed profile of each vehicle type). This method will also capture delay that is caused by platoons. If for example a vehicle with speed profile 30 km/h is stuck behind a slower vehicle, the delay experienced for that trailing vehicle is added to the total delay.

It is hypothesised that the relationship between the number of vehicles and the delay is non-linear, as the time needed to pass an intersection is expected to grow disproportionally as volume increases. Pre-analysis has shown that the relationship between the number of vehicles (independent) and total delay (dependent) is indeed exponential rather than linear. The plots showing this relationship have been presented in appendix B. Therefore, the natural logarithm of total delay has been taken, leading to a linear relationship between the dependent and independent variable. This results into the following linear regression model for each infrastructure component:

$$\ln(\mathsf{D}_j) = \beta_{0j} + \sum_{i \in I} \beta_{ij} \cdot \mathsf{N}_i \qquad \forall j \in J \tag{6.1}$$

where:

D_j : Total delay of infrastructure component j

β_{0j} : Regression constant (intercept) of infrastructure component j

β_{ij} : Regression coefficient of vehicle type i and infrastructure type j

N_i : Number of vehicles of type i

With this model, a prediction can be made for the total delay of each intersection, based on the number of vehicles of each type passing it. Moreover, the relative impact of each vehicle on traffic performance can also be calculated. This is the actual calculation of de PCU. The PCU of a vehicle type i at infrastructure component j is calculated by dividing the regression coefficient of that vehicle by the regression coefficient of the passenger car. In this manner, the regression coefficients are calculated for each vehicle, but also for each infrastructure component, resulting in 55 (11 vehicles and 5 components) unique PCU calculations. The following mathematical formulation describes this:

$$\text{PCU}_{ij} = \frac{\beta_{ij}}{\beta_{\text{car}j}} \qquad \forall i \in I, \forall j \in J \tag{6.2}$$

where:

PCU_{ij} : Passenger Car Unit of vehicle type i at infrastructure component j
$\beta_{\text{car}j}$: Regression coefficient of vehicle type passenger car at infrastructure component j

6.1.1. VISSIM experiment setup

The VISSIM models for the PCU-analysis will be set up as described in Chapter 5, where the input parameters for the VISSIM models are explained. The "base case" traffic composition is also used for this analysis. The total traffic volume is set at 200 vehicles per hour at first. This traffic volume is increased incrementally with steps of 150 vehicles per hour. For each volume level, the number of vehicles of one of the eleven vehicle types (including reference point passenger car) will be increased by 20% of the total volume of that scenario. All other parameters and input will be kept constant. This setup results into twelve different scenarios for each volume-level that can be used to effectively analyse the influence of adding extra vehicles of a certain type to the total delay of that simulation.

6.1.2. Expected results

Using the previously explained approach and settings, this analysis is expected to generate accurate PCU values for the different service vehicles. If the VISSIM simulation outputs correctly represent the physical and behavioural parameters of the service vehicles, the results are expected to give consistent PCU distributions across the different infrastructure components. In general, this means that the order of PCU values within each intersection or segment will approximately be the same. If for example a baggage train - which is a large, slow vehicle with low manoeuvrability - has the highest PCU value at a four-way priority intersection, but a much lower relative PCU at a three-way priority intersection, this is inconsistent. This might indicate invalid PCU values as a result of the methodology that is chosen within this research.

Furthermore, this analysis tests whether there is a (substantial) difference of the actual PCU values between different infrastructure component. As many research considers a fixed or generalised PCU value across entire roadway facilities [52], this research aims to find whether there is a different influence of a vehicle type depending on the type of intersection. It is expected that, due to variations of the VISSIM models, the PCU values are not exactly the same. There is no general expectation of higher relative PCU values for a certain infrastructure component. However, it is hypothesised that the average PCU of an entire infrastructure component is not consistent, as heavy vehicles are presumed to perform differently across the different intersections.

6.2. Results

The results from the PCU analysis have been summarised in Table 6.1 and Figure 6.1. Table 6.1 presents all PCU values for each vehicle type included in the model, for each infrastructure component. Figure 6.1 graphically presents the PCU values, highlighting the differences within (different infrastructure components) and between different vehicle types. The statistical results from the MLR models are reported in Appendix B.

The results of this analysis show the PCU of a certain vehicle type can differ significantly between different infrastructure components, as was also hypothesised. For example, a baggage train has a PCU of 3.53 at the four-way priority intersection, while it is only 2.29 at the four-way roundabout. This insight reveals that the impact of any vehicle type on traffic performance differs across different types of intersections, also while considering the associated regression coefficients. The regression coefficients are reported in Figure B.3.

The average of the infrastructure components have also been presented to prove that there is a substantial difference between the infrastructure components. The results from the four-way priority intersection show the highest PCU values of all intersection components. This indicates that the service

Table 6.1: Passenger Car Unit for all vehicles and infrastructure components

Vehicle type	4-way prio.	4-way round.	3-way prio.	3-way alt.	Main road
Car (reference)	1.00	1.00	1.00	1.00	1.00
Bus	2.35	1.66	1.71	1.74	1.45
Catering truck	2.23	1.60	1.80	1.92	1.35
Fuel truck	2.63	1.67	1.85	1.75	1.67
Cleaning van	1.52	1.04	1.32	1.33	1.05
Toilet/water truck	2.38	1.48	1.80	1.70	1.21
Baggage train	3.53	2.29	2.61	2.51	2.20
Cargo train	3.67	2.33	2.70	2.48	2.21
Push-back tractor	2.14	1.31	1.61	1.63	1.95
Belt loader	2.45	1.29	1.59	1.51	1.65
High loader	2.94	1.53	2.26	2.08	1.89
Avg. (excl. Car)	**2.58**	**1.62**	**1.93**	**1.87**	**1.66**

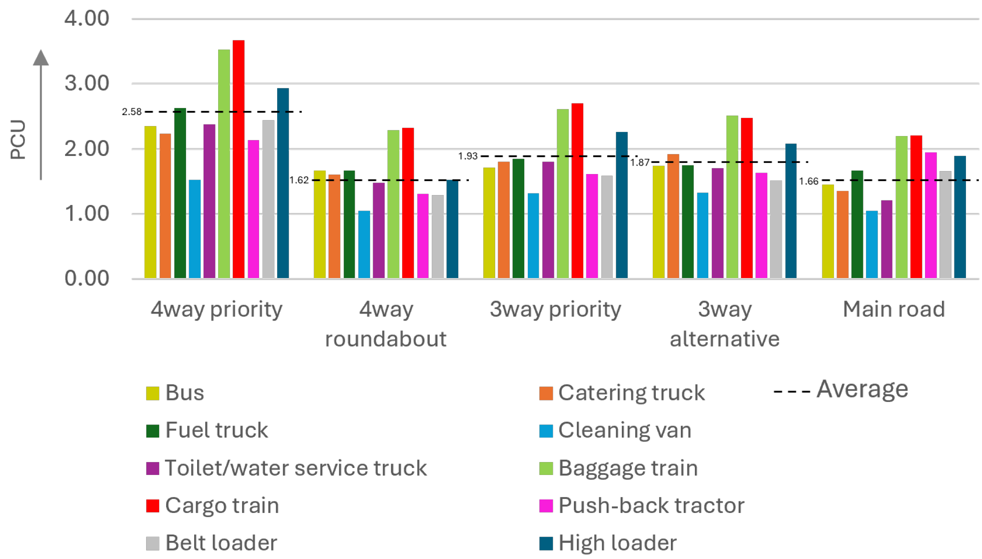


Figure 6.1: Passenger Car Unit for all vehicle types and infrastructure components

vehicles at this type of infrastructure component have a greater influence on traffic performance compared to passenger cars than at other components. The four-way roundabout on the other hand, is much more indifferent to the vehicle types, as PCU values are notably lower compared to the four-way priority intersection. This result suggests that roundabouts are able to facilitate smoother traffic when the traffic composition is heavy in general, as is the case with service roads. These differences between infrastructure components mean that it is highly complex to generalise PCU values across the entire service road networks. Furthermore, it highlights the importance of looking at service road networks by decomposing them into smaller segments (i.e. infrastructure components).

Comparing both three-way intersections with each other, it reveals that the PCU values of both configurations are rather similar. This indicates that the performance of service roads relative to the passenger car is very similar. This analysis has not yet revealed significant differences between the two three-way intersections. Further analysis in terms of capacity (Chapter 7) and LoS (Chapter 8 and 9) will give more insights on the relative performance of these intersections. The PCU values of main road segments are similar to three-way intersections, although slightly lower on average. This suggest that the impact of different vehicle types becomes less notable if multiple three-way priority intersections are placed near each other.

Lastly, the distribution of PCU values are largely consistent between the different infrastructure components, therefore behaving as expected. Some minor deviations exist, such as the push-back tractor having a slightly lower PCU value compared to a belt loader at four-way priority intersections, while having a a slightly higher value compared to the same vehicle at main road segments. The push-back vehicle is a slightly larger vehicle, and it is assumed that this small deviation can be attributed to randomness from the simulation models. These deviations are small and ultimately do not influence the accuracy of the PCU values drastically.

To illustrate the consistency more clearly, Figure 6.2 is created. This overview shows the percentage difference of all the vehicle types compared to the average of the infrastructure components. Ideally, the percentage difference should be close to zero, as this indicates that the distribution and therefore the PCU values are consistent across the different infrastructure components. This was also expected from the results to a certain extent. Figure 6.2 shows that indeed, most PCU values are centred around zero. 84.0% of the PCU values have a deviation of 10% or less compared to their corresponding average, and 98.0% have a deviation of 20% or less. The largest deviation is the push-back tractor at main roads, which has a percentage difference of +29.5%. Although this difference is still between reasonable limits, there is no real logic found why this specific vehicle has a larger difference compared to others. It is therefore assumed that this findings is result of the randomness in the VISSIM models.

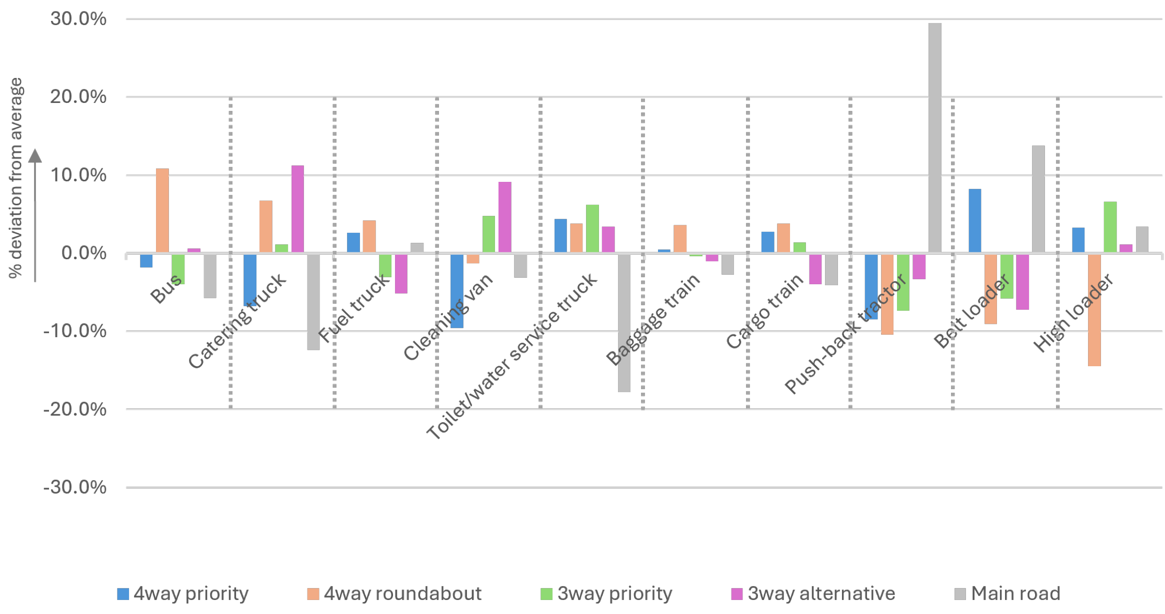


Figure 6.2: Percentage difference compared to infrastructure component average

6.3. Chapter conclusion: Passenger Car Unit of service vehicles

The PCU values of the service vehicles are calculated for each infrastructure component included in this research. The PCU values have been presented in Table 6.1, effectively providing an answer to research question 1(b). These results are useful for future research, as this is the first calculation of PCU values for service vehicles found in the literature. The results have shown that PCU values differ significantly between the infrastructure components. This implies that generalising PCU values across entire networks (assigning an overall PCU value per vehicle) is challenging, as the relative performance of vehicles varies depending on the type of infrastructure component. This highlights the importance of analysing intersections independently. Results have shown that service vehicles on four-way priority intersections have a substantially poorer performance relative to the passenger car, compared to a four-way roundabout which is much more indifferent to the characteristics of service vehicles. This indicates that the roundabout is more efficient at handling service vehicles than four-way priority intersections. Three-way intersections also show relatively low PCU values compared to four-way priority intersections, indicating vehicle delays are lower at identical volume rates in terms of vehicles per hour.

7
Capacity of service road components

The capacity analysis follows a similar structure as previous chapter (PCU calculation). First, the approach for determining the capacity is described in Section 7.1, including the VISSIM experiment settings and the results that are expected. Next, the results are presented and interpreted in Section 7.2. Lastly, a chapter conclusion is written (Section 7.3) that is specifically addressing research question 1(c), which is interested in the capacity of infrastructure components expressed in PCU per hour.

7.1. Analysis approach

This Section explains how the capacity of the different infrastructure components is measured. It is important to note that this analysis determines the capacity rather than the maximum flow rate. The difference between the two is that capacity measures the maximum sustainable hourly flow rate, meaning that it measures the performance that could reasonably be expected [58]. The maximum flow rate is the highest flow rate that is observed over each simulation run. Since these traffic models have underlying stochastic processes, using maximum flow rate could results into a flow rate that is an outlier and thus can be unrepresentative for the performance of such systems.

Before this analysis starts, it has been hypothesised that traffic volume input and capacity show asymptotic behaviour, meaning that any input volume larger than the actual capacity results in the same output in terms of vehicles per hour, given the same traffic composition. This is known as over-saturation of the infrastructure, which causes an unstable traffic system with growing queues over time [17]. Prior analysis of the four-way intersection reveals the relationship between input (volume) and output. This has been presented in Figure 7.1. This Figure shows that the output value stagnates as it reaches its theoretical capacity. This means that any input value substantially larger than the capacity can be chosen to obtain the capacity value (the right hand side of the graph). As it is unknown prior to analysis where this value exactly lies, the input is set at 4000 vehicles per hour, which is an unrealistic demand that can not be achieved under any circumstance. The vehicle composition of the “base case”, which has been described in Section 5.1, is initially used for this analysis. All other parameters and input from the “base case”, as described in the VISSIM model input (Chapter 5, are used for this analysis.

In VISSIM, the capacity is determined using node analysis. Across the duration of the simulation run (1 hour and 3 minutes, 3 minute warm-up time), the number of vehicles of each type passing the infrastructure component is measured. The simulation is repeated with the same input twenty times to obtain reliable estimations, which is considered to be sufficient taking into consideration the low degree of variability when over-saturating the model. The number of vehicles of each vehicle type is then averaged over all simulations. Lastly, the capacity, in terms of PCU per hour, is calculated using formula 7.1.

$$\text{CAP}_j = \sum_{i \in I} \text{PCU}_{ij} \cdot \text{N}_i \qquad \forall j \in J \tag{7.1}$$

where:

CAP_j : Capacity of infrastructure component j

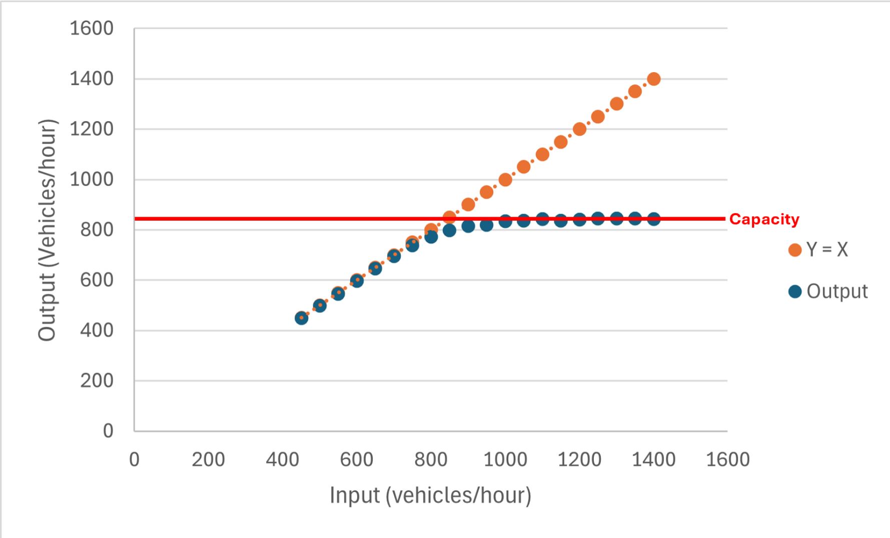


Figure 7.1: Results input-output four-way intersection

7.1.1. VISSIM experiment setup

To verify that the estimation of the capacity is applicable to various environments, it is tested with varying traffic compositions. Other than the "base case" composition, which has been determined in Chapter 5 where all VISSIM input is explained, three other compositions are deployed in this analysis. The first one is called "Equal", and represents all vehicle types (including passenger car) with equal share. Secondly, the "Inverted" traffic composition is the inverse of the "base case" composition, meaning that the vehicle with the highest share in the "base case" has the lowest share (proportionally) in the "inverted" composition. Lastly, a stress test is performed by implementing a "Passenger car only" composition. This indicates whether the results are still reliable with a more extreme values for traffic composition, even though this traffic composition is typically not found on airport service roads.

Additionally, it is hypothesised that a varying composition leads to similar results, because the concept of PCU in general is that its value should give an indication of the performance of this vehicle type relative to passenger cars. However, it is important to analyse this, since the PCU values in this research are calculated using total delay, and not capacity. This analysis therefore validates if the PCU values obtained from the previously described MLR analysis are also applicable when determining the capacity.

7.1.2. Expected results

Since PCU is a standardised unit that captures the influence of any vehicle type compared to a passenger car, it is expected that the results are consistent across the different traffic compositions. This therefore validates that the PCU values can be generalised to various airports appropriately. If this is not the case, it can limit the applicability of this methodology. However, since the MLR models capturing the different PCU values are not perfect, small deviations are still expected.

Furthermore, conclusions regarding the capacities expressed in PCU per hour should be made with caution. This is because the actual PCU values are calculated for the infrastructure components individually, which has been explained in the corresponding PCU analysis Chapter 6. It can therefore be theoretically possible that the capacity in PCU per hour is relatively lower, while the actual capacity in terms of vehicles per hour (given the same traffic composition) is actually higher. This is for example expected for the PCU capacity of a four-way roundabout, since this has significantly lower PCU values compared to its counterparts. The outcome of the analysis (expressed in PCU per hour) is however still useful input for the performance estimation, which is explained in Chapter 8.

Following the results of the PCU values (Chapter 6), it is expected that roundabouts perform significantly better than four-way priority intersections. Not only were the lowest PCU values observed for this infrastructure component, this type of intersection also has significantly less conflict points. It is hypothesised that this is particularly beneficial for heavy service vehicles, since these have large intersection clearing times. The three-way priority intersection is expected to perform better than the alternative three-way configuration, since the priority-based intersection gives priority to more conflicts.

7.2. Results

This section presents the results of the capacity of the different infrastructure components as previously described in this chapter. The results have been summarised in Table 7.1.

Table 7.1: Capacity (PCU/hour) for all composition scenarios

Composition	4-way prio.	4-way round.	3-way prio.	3-way alt.	Main road
Base case	2043.50	1561.56	1669.19	1338.55	1288.12
Equal	2050.23	1556.31	1653.57	1328.52	1351.70
Inverted	2061.10	1536.99	1658.45	1316.78	1430.58
Passenger car only	1925.00	3088.00	1837.00	2049.00	2041.00
Avg. (excl. Car only)	**2051.61**	**1551.62**	**1660.40**	**1327.95**	**1356.80**

First, the results show that "Passenger car only" composition generates remarkable results for the four-way priority, the three-way alternative and main road in particular, as the capacity in terms of PCU per hour differs significantly compared to the other three compositions. This is contrary to what was expected, since PCU values are expected to capture the impacts of the different vehicles consistently. However, the "Passenger car only" composition is also the most extreme and unrepresentative composition for service roads. The three other compositions on the other hand, represent all vehicle types and are therefore more likely to represent actual service road traffic. Between these three compositions, the capacity in terms of PCU per hour are very comparable, with a maximum deviation of 11.0% between main road "base case" and "inverted". The largest difference in general (excluding "passenger car only") is measured between the "base case" and "inverted", which can be explained because these compositions are each others inverse. Even under these diverse compositions, the difference is small, with a deviation of 0.8%, 1.6%, 0.6%, 1.7% for four-way priority, four-way roundabout, three-way priority and three-way alternative intersections respectively. Because these traffic compositions are deemed more representative, the average of the three compositions have been calculated and used for further analyses. These are essential for the determination of LoS in Chapter 8.

It is important to note that in Table 7.1 it is not possible to compare capacities between different infrastructure components directly, since capacities in this table have been calculated in PCU per hour, and every model has different estimated PCU values per vehicle type (see the results of the PCU values in Section 6.2). This is also explained in the expected results (Section 7.1.2). Having higher PCU values for vehicle types results into higher capacities in terms of PCU per hour, while it is possible that in terms of vehicles per hour (given the same traffic composition), the capacity is actually lower.

To illustrate this, Figure 7.2 has been created. In contrary to Table 7.1, this can be used to compare the performance throughput of the different infrastructure components, because this measures the absolute capacity in terms of vehicles per hour, while the traffic compositions are kept fixed. The "Passenger car only" composition, due to its single, significantly better-performing vehicle type and consistently high throughput, has been excluded from this overview. This illustration focuses on the compositions "Base case", "Equal", and "Inverted", which are deemed more representative for service roads.

On average, the four-way roundabout has the highest capacity of 998.7 vehicles per hour, followed by the three-way priority intersection (890.0 vehicles per hour). A main road, which is effectively a series of three three-way priority intersections in this part of the research, has a capacity of 839.7 vehicles per hour, which is lower than the capacity of a single three-way priority intersection. The four-way priority

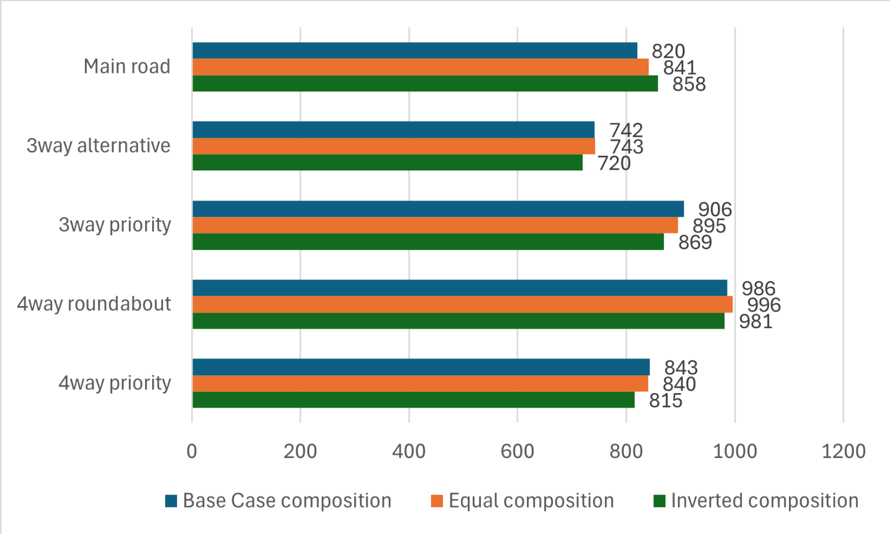


Figure 7.2: Capacity (vehicles/hour) for representative traffic compositions

intersection performs considerably worse than a roundabout, with a capacity of 832.7 vehicles per hour. Lastly, the three-way alternative intersection has a capacity of 735.0 vehicles per hour.

Notably, the four-way roundabout indeed performs best, while in Table 7.1 it has a lower throughput in terms of PCU per hour compared to four-way priority and three-way priority intersections. This was also expected prior to this analysis. This can be explained by the relatively low PCU values that are previously calculated in Table 6.1. This highlights the importance of comparing the infrastructure components in terms of vehicles per hour, as this makes the performance indifferent to PCU values.

When comparing both types of three-way intersections, it is noted that the alternative configuration performs significantly worse compared to the traditional priority intersection. This was also the case in terms of PCU per hour, as PCU values of both infrastructure components were comparable. This conclusion could however not be drawn based on the PCU values calculated in Chapter 6, as both infrastructure components generated very similar PCU values. The average PCU value of three-way priority intersection was 1.93, while for three-way alternative intersections it was 1.87. The reduced capacity of the alternative intersection can be explained, since more vehicle movements have to give priority in this configuration compared to the priority counterpart.

Lastly, it is interesting to study the difference in throughput between the main road segment and the three-way priority intersection. In the manner it was modelled, the main road segment is in fact a series of connected three-way priority intersections. The capacity of the main road segment with three stands is slightly lower than the capacity of the three-way priority intersection. This is the effect of having multiple infrastructure components positioned closely too each other. Since this can influence the performance of individual intersections, it is important to also analyse service roads on a larger scale, since connected intersections can have an effect on each other. This analysis is performed in Chapter 9. The reduced capacity for main roads can be explained through the dependence of the individual intersections: the weakest performing intersection can form a bottleneck, limiting the traffic flow upstream as well. Research on upstream capacity affected by downstream queues on urban intersections [63] also states that the the effectiveness of the upstream intersections is reduced because of traffic spill-backs, especially when there is a short distance between intersections and traffic is dense.

7.3. Chapter conclusion: capacity of infrastructure components

The capacity analysis, from which the findings are reported in Table 7.1 and effectively answers research question 1(c) (capacity of infrastructure components expressed in PCU per hour), has shown that capacity in terms of PCU per hour is slightly dependent on the actual traffic composition, meaning that the estimated PCU values do not capture traffic heterogeneity perfectly. This is to be expected, since the MLR model is a simplified representation estimating the performance of service roads based on delay rather than the capacity. Although the PCU is measured using an indicator that reflects a different aspect of infrastructure performance, it can consistently estimate capacity as well.

The results of the analysis show that the capacity in terms of PCU per hour per infrastructure component are very comparable for a diverse range of traffic compositions. More extreme conditions however show that there is a significant capacity difference in terms of PCU per hour for the same infrastructure component, which indicates that the model is not robust enough to provide constant outcomes under all conditions. This limits the applicability of the methodology, but given the fact that a extreme composition such as the “passenger car only” (which was tested in this case) is not representative and not present at any type of service road network, the impact of this limitation is minimal. In conclusion, the capacity in terms of PCU per hour for all infrastructure components can be used for further analyses, given that service roads operate under more representative conditions during these analyses and in reality.

Furthermore, the capacities per infrastructure component are compared in terms of vehicles per hour, while traffic conditions on all components are identical. On average and as predicted, the four-way roundabout demonstrated the highest capacity, accommodating 998.7 vehicles per hour. This was followed by the three-way priority intersection, which managed 890.0 vehicles per hour. Interestingly, the main road, which in this part of the research is considered as a series of three priority intersections, had a lower capacity of 839.7 vehicles per hour compared to a single three-way priority intersection. The four-way priority intersection performed significantly worse than the roundabout, with a capacity of 832.7 vehicles per hour. Lastly, the three-way alternative intersection had the lowest capacity, handling 735.0 vehicles per hour.

8

Level of Service determination of infrastructure components

This chapter again follows the same structure as previous Chapters 6 (PCU) and 7 (capacity). The methods for assessing the performance of service road components using a LoS metric are presented in 8.1, including a description of the VISSIM experiment setup and the expected results. Hereafter, the results of the LoS analysis are presented and interpreted in Section 8.2. Additionally, an explanation on how the findings from the analyses thus far can be used in practice is given in Section 8.3. A chapter conclusion is written (Section 8.4) that specifically addresses research sub-question 1(d), which is interested in finding the boundaries (expressed in PCU per hour) that separate the different service levels.

8.1. Analysis approach

According to the HCM [58], delay is considered to be the most appropriate way for determining the LoS of intersections. As delay can be extracted from the data of the VISSIM-models, using this measurement is a good fit for the purpose of this analysis. Furthermore, as delay is also used to calculate the PCU values within this research, an estimation of the LoS can also be obtained based on the MLR models that have been presented in Chapter 6, that served as a basis for the PCU calculations. (Total) delay has been intentionally selected for these analyses to align with the HCM requirements for intersection LoS. This approach provides a comprehensive method capable of delivering reliable estimations with minimal input requirements. The LoS method is graphically presented in Figure 8.1, showing which processes take place and which sub-results flow out of these processes. An explanation of the method is given afterwards.

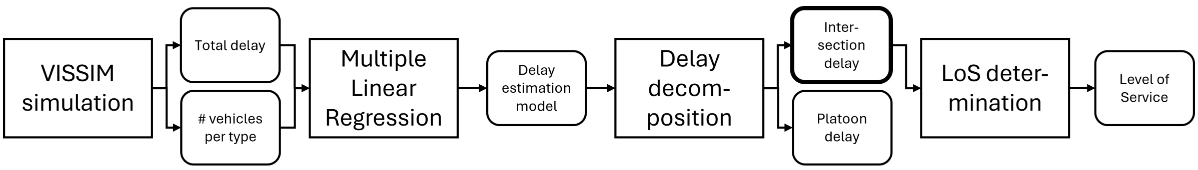


Figure 8.1: Method for determining Level of Service of different infrastructure components

First, VISSIM simulations are performed using the VISSIM model input parameters presented in Chapter 5. The VISSIM simulation results into two important outputs: Total delay and the number of vehicles per vehicle type. Then, the method for MLR described in the approach for determining the PCU values 6 is applied to this analysis. This analysis does not include the actual determination of the PCU values as described in that chapter, but rather uses the obtained MLR model and its regression coefficients. This is described in Formula 6.1, which is also again presented underneath. This formula is used to calculate the expected total delay.

$$\ln(\mathsf{D}_j) = \beta_{0j} + \sum_{i \in I} \beta_{ij} \cdot \mathsf{N}_i \qquad \forall j \in J \tag{8.1}$$

where:

D_j : Total delay of infrastructure component j
β_{0j} : Regression constant (intercept) of infrastructure component j
β_{ij} : Regression coefficient of vehicle type i and infrastructure type j
N_i : Number of vehicles of type i

8.1.1. Delay decomposition

The next step is to decompose the delay of the infrastructure pieces. For intersections, the HCM [58] considers pure intersection delay (also called control delay) to be the main indicator for the LoS an intersection can provide. The delays estimated from the MLR model does however also include another component of the total delay: platoon delay. Within this context, a platoon of vehicles is a series of vehicles travelling closely to each other, where the speed of the following vehicles are limited by the speed of the leading vehicle. The leading vehicle is in free flow and therefore does not experience any delay, while the following vehicles are impeded by the leader. This type of delay is not attributable to the intersection itself, but is rather a result of the heterogeneity of traffic. Therefore, the total delay D_j calculated in equation 8.1 should be corrected for platoon delay.

To obtain platoon delay, a simple VISSIM simulation is set up. Since all intersection simulations are performed with identical link sizes and a measurement area of 270 meter, a straight segment of the same size without any interruptions (i.e. intersections) is modelled. The same is done for the main road segment, but with corresponding link lengths. All else being equal, the delay and number of vehicles resulting from the straight segment simulation can be put in a MLR model in an identical manner as previously explained in Section 6.1, the approach for the PCU analysis. This also generates a regression model that can predict the occurred total platoon delay. The intersection delay D_j^{int} is then calculated by Formula 8.2. It is important to note that for the main road segment, the intersection delay is the delay of the entire road segment (i.e. multiple intersections). The platoon delay is therefore corrected for the length of the trajectory. Also, the estimated platoon delay following the MLR model can (in theory) be a negative number, which is not realistic. To correct for this, the platoon delay is considered to be a minimum value of zero under all circumstances.

$$D_j^{\text{int}} = D_j - \max(0, D_j^{\text{plat}}) \qquad \forall j \in J \tag{8.2}$$

Lastly, the vehicle delay D_j^{veh} is calculated by dividing the intersection delay D_j^{int} by the total number of vehicles N.

$$D_j^{\text{veh}} = \frac{D_j^{\text{int}}}{\sum_i N_i} \qquad \forall j \in J \tag{8.3}$$

8.1.2. Level of Service determination

The last step is to determine the actual LoS of the infrastructure component. This is done according to the HCM [58]. For intersections, the LoS is expressed in terms of seconds of intersection delay D_j^{int} per vehicle, which is called “Control delay” in the HCM. HCM has specifically formulated the criteria for unsignalised four-way intersections, which have been presented in Figure 8.2. To ensure a stable traffic system and representative results, the HCM has formulated another constraint to the LoS-determination. This describes that the volume V_j of the infrastructure component j should not exceed the capacity CAP_j in terms of PCU per hour. This PCU-capacity has previously been calculated in Chapter 7. The HCM automatically assigns LoS “F” when capacity is exceeded. A further explanation will be given on how this framework is used for the other infrastructure components.

Control Delay (s/ vehicle)	LOS by Volume-to-Capacity Ratio	
	$v/c \leq 1.0$	$v/c > 1.0$
0–10	A	F
> 10–15	B	F
> 15–25	C	F
> 25–35	D	F
> 35–50	E	F
> 50	F	F

Figure 8.2: Level of Service criteria of four-way intersections based on the Highway Capacity Manual [58]

For three-way intersections, it is assumed that the tolerance for delay is lower since there are less conflicting pathways compared to four-way intersections. A typical four-way intersection has 32 conflict points, while a typical three-way intersection only has 9. Research on unsignalised intersections [64] has also indicated that the delay decreases when the number of conflicts decrease, which indicates the validation of this assumption. There is no general heuristic available as to how much the delay decreases with each extra conflict, as this is also dependent on other traffic factors [64].

For three-way intersections it has been decided to lower the delay boundaries between the different levels of service by 2 seconds compared to what the HCM [58] has formulated for four-way intersections. It has been purposefully chosen to maintain the same LoS criteria ranges, therefore lowering each criteria boundary in seconds rather than with a certain percentage. The LoS criteria ranges have been determined based on user experience [58], which falls outside the scope of this research. Using a fixed two second lowering of the LoS criteria boundaries ensures consistency with the principles of the HCM. Specifically 2 seconds is chosen as a conservative estimate that aligns with these principles, ensuring that the criteria are neither too lenient nor too stringent. The resulting criteria for four-way and three-way intersections are presented in Table 8.1.

The main road is not one single intersection and therefore, the delay is dependent on the number of stands (i.e. intersections) placed on the main road segment. The HCM [58] does not consider delay as the indicator for infrastructure performance of this type, but average travel speed as a percentage of the base free flow speed. However, for reasons of uniformity, it is desired to also express the main road segment in terms of delay. The straight road segment can be considered as multiple adjacent three-way intersections. However, since it is a main road with a significant amount of through-traffic, the tolerance for delay is assumed to be low, as it can have a notable impact on the timely arrival of service vehicles. Additionally, each stand or intersection has an influence on the next stand (intersection) downstream.

In a similar manner as explained for three-way intersections, it has been decided to use the same framework as for 4-way intersections, but with 5 seconds less tolerance per service level boundary. It is argued that because of the high share of through traffic and the closely, in sequence positioned intersections should lead to a significant less delay per intersection compared to four-way and three-way intersections. The resulting criteria have also been presented in Table 8.1. Note that this is seconds of delay per vehicle per aircraft stand, meaning that a delay of 12 seconds for a main road segment with 3 stands is considered to be LoS “A”, as this is 4 seconds of delay per aircraft stand.

A more analytical approach for setting the LoS boundaries based on studies capturing user experience for different intersection types is recommended in the future, but is not possible within the limited time frame of this research. For this study, the criteria of the four-way intersection based on the HCM and the reasoning for adapting the boundaries in the described manner is deemed acceptable for now, as they maintain within a acceptable range described in the HCM.

8.1.3. VISSIM experiment setup

The LoS analysis aims to find the boundaries in terms of PCU per hour from which the LoS switches from one service level to another, which are called LoS boundaries. When the results are valid, these boundaries can be applied to service road intersections on airports. Since the PCU values are obtained using an MLR model, which is an imperfect representation of reality and is therefore unable to capture the relative impact of any vehicle type to another, it is important to understand how sensitive the LoS boundaries are to variations of traffic compositions. Ideally, the model is insensitive to different traffic

Table 8.1: Level of Service criteria intersection delay for each infrastructure component, [58]

Level of Service	4-way prio. [s/vehicle]	4-way round. [s/vehicle]	3-way prio. [s/vehicle]	3-way alt. [s/vehicle]	Main road [s/vehicle/stand]
A	0 - 10	0 - 10	0 - 8	0 - 8	0 - 5
B	10 - 15	10 - 15	8 - 13	8 - 13	5 - 10
C	15 - 25	15 - 25	13 - 23	13 - 23	10 - 20
D	25 - 35	25 - 35	23 - 33	23 - 33	20 - 30
E	35 - 50	35 - 50	33 - 48	33 - 48	30 - 45
F	> 50	> 50	> 48	> 48	> 45
F	$V_j > CAP_j$	$V_j > CAP_j$	$V_j > CAP_j$	$V_j > CAP_j$	$V_j > CAP_j$

compositions, making the model robust and applicable to various airport environments.

To test this, a VISSIM experiment is created. Similar to the experiment set up for the capacity analysis, four different traffic compositions are tested: “Base case”, “equal”, “inverted” and “passsenger car only”. The first three are deemed representative as they include all vehicle types with different distributions, offering a wide variety of possible combinations that can be present on airport service roads. “Passenger car only” is again tested on the VISSIM models to assess its performance under extreme conditions.

8.1.4. Expected results

The aim of this research is to create a standardised methodology applicable to different airport environments. Consequently, this analysis does not include performance estimations for real-life service road intersections. Instead, it provides an efficient and easy-to-use table that enables airport operators to evaluate the performance of airport-specific traffic scenarios, based on the mechanisms detailed in this research. The table estimates the LoS based on PCU flows (i.e. expressed in PCU per hour), which can be derived from traffic counts. Effectively, an overview is given indicating the boundary levels expressed in PCU per hour that separate different service levels (“A” to “B”, “B to “C”, etc.). In other words, the LoS is determined based on volume levels, which is also being done in the literature. Research on comparing methods for determining the LoS of roadways [24] indicates a potential for determining the LoS based on the volume-to-capacity ratio. The expectations of this analysis are limited, because the analysis merely generates a framework based on prior analyses.

However, multiple traffic compositions are tested for this analysis. It is expected that the LoS boundaries are largely consistent across the different compositions. Small variations are possible due to the imperfect nature of the PCU values, which has also been concluded in the capacity-analysis (Chapter 7). It is furthermore expected that the largest deviations come from the “passenger car only” composition, since this one is the most extreme compared to the other compositions.

Additionally, it is expected that the capacity constraint (which has been presented in Table 8.1 in the approach of this analysis) does not come into effect under most circumstances. However, it is theoretically possible that certain delay levels are outside the bounds of the capacity-constraint, since the delay is calculated using a MLR prediction model, while the capacity is determined directly from the VISSIM models. Due to discrepancies between the two methodologies, it is possible that capacity is reached at certain boundary levels. If this is the case, the boundary-level is reported as “‘N/A”.

8.2. Results

The results from the LoS analysis are presented in this section. The results can be found in Table 8.2. For each of the infrastructure components analysed, the boundaries for the different levels of service in terms of PCU per hour have been presented. This has been repeated for four different vehicle compositions: “Base Case”, “Equal”, “Inverted” and “Passenger car only”. Note that the constraint describing that LoS is assigned level “F” if capacity is exceeded is included in this overview, based on the capacity reported in the capacity analysis (Chapter 7, Table 7.1).

Table 8.2 is an analysis to detect the boundaries between different levels of service for each infrastructure component, while considering different traffic compositions. The LoS boundaries within the

Table 8.2: Level of Service boundaries (PCU/hour) for all infrastructure components

LoS	Base case [PCU/hour]	Equal [PCU/hour]	Inverted [PCU/hour]	Passenger car only [PCU/hour]
		4-way priority		
A	< 1356	< 1319	< 1239	< 1858
B	1356 - 1452	1319 - 1422	1239 - 1368	1858 - 1917
C	1452 - 1587	1422 - 1568	1368 - 1528	1917 - 1925 (CAP)
D	1587 - 1684	1568 - 1668	1528 - 1634	N/A
E	1684 - 1795	1668 - 1780	1634 - 1753	N/A
F	> 1795	> 1780	> 1753	> 1925 (CAP)
		4-way roundabout		
A	< 1014	< 998	< 961	< 1271
B	1014 - 1104	998 - 1092	961 - 1065	1271 - 1334
C	1104 - 1226	1092 - 1220	1065 - 1202	1334 - 1434
D	1226 - 1314	1220 - 1310	1202 - 1298	1434 - 1511
E	1314 - 1413	1310 - 1412	1298 - 1402	1511 - 1602
F	> 1413	> 1412	> 1402	> 1602
		3-way priority		
A	< 1156	< 1126	< 1061	< 1467
B	1156 - 1242	1126 - 1220	1061 - 1173	1467 - 1526
C	1242 - 1361	1220 - 1347	1173 - 1312	1526 - 1621
D	1361 - 1447	1347 - 1436	1312 - 1408	1621 - 1695
E	1447 - 1544	1436 - 1537	1408 - 1513	1695 - 1781
F	> 1544	> 1537	> 1513	> 1781
		3-way alternative		
A	< 1089	< 1065	< 1008	< 1397
B	1089 - 1179	1065 - 1162	1008 - 1121	1397 - 1458
C	1179 - 1301	1162 - 1290	1121 - 1263	1458 - 1553
D	1301 - 1339 (CAP)	1290 - 1329 (CAP)	1263 - 1317 (CAP)	1553 - 1627
E	N/A	N/A	N/A	1627 - 1715
F	> 1339 (CAP)	> 1329 (CAP)	> 1317 (CAP)	> 1715
		Main road segment		
A	< 1161	< 1117	< 1053	< 1188
B	1161 - 1275	1117 - 1244	1053 - 1199	1188 - 1335
C	1275 - 1288 (CAP)	1244 - 1351 (CAP)	1199 - 1370	1355 - 1515
D	N/A	N/A	1370 - 1431 (CAP)	1515 - 1633
E	N/A	N/A	N/A	1633 - 1758
F	> 1288 (CAP)	> 1622	> 1431 (CAP)	> 1758

different infrastructure components are not fully consistent. For example, LoS “A” for the 4-way priority intersection has 1356, 1319, 1239 and 1858 PCU per hour as the upper limit for “Base Case”, “Equal”, “Inverted” and “Passenger car only” traffic compositions respectively. This means that the traffic composition does have an influence on the strict LoS of the roads.

As expected, “passenger car only” shows the greatest variability when compared to the three other traffic compositions. This traffic mix is purposefully included in this analysis to test the model under extreme conditions. Service roads are typically not exclusively used by passenger cars, so conclusions from this result should carefully be drawn. The significant deviation can be attributed to the relatively high performance of the passenger car, which, unlike other service vehicles, possesses good manoeuvrability.

The three other traffic compositions (“Base Case”, “Equal” and “Inverted”) do however show more similar results within the same infrastructure component. These compositions represent more realistic traffic on service roads and contain every vehicle type included in this research. The difference between “Base Case” and “Inverted” is the largest, but with a largest deviation of 10.26% (Main road segment, LoS “A”), the variability is within reasonable limits. This means that under representative compositions - which is the case at airport environments - the LoS determination based on PCU flows are sufficiently accurate.

Table 8.2 also shows that variability between different traffic compositions decreases when the LoS decreases, with the lowest LoS being “F”. For the intersections, the maximum deviation in terms of PCU per hour between “Base Case” and “Inverted”, which are both considered representative traffic mixes, is only 2.50% for LoS “F”. This indicates that the impact of traffic composition is less notable on higher traffic volumes, and the resulting LoS boundaries are therefore more similar. This phenomenon can be explained, since the infrastructure components operate at or near capacity under LoS “F”. Previous capacity analyses (Chapter 7) has shown a large consistency between the different capacities. At optimal service levels, roads are more in a free-flow state, allowing each vehicle more flexibility to manoeuvrer. This leads to greater variability among different vehicle types.

The variability is explained by the method for determining the delay per vehicle. Two separate combinations of traffic composition and traffic volume can both result in the same output in terms of PCU per hour, leading to the same total delay for both combinations. However, since the delay per vehicle is calculated by dividing the total delay by the traffic volume (which are two unique values for the two combinations), the resulting delay per vehicle is different in each case. For example, a volume of 600 vehicles per hour with the “Base Case” composition results in the same total delay as a volume of 571 vehicles per hour with the “Inverted” composition, as well as identical flows in terms of PCU per hour. But since the total number of vehicles are different, the resulting delay per vehicle is also different, leading to small differences in the boundary values.

As previously mentioned, the HCM considers one extra criteria for LoS “F”. This criterium describes that any infrastructure component gets LoS “F” assigned to it if the traffic volume of the estimated model exceeds the capacity of the particular component. Based on this analysis and the capacity results presented in Chapter 7 (capacity analysis), it can be concluded that several cases observe higher traffic volumes based on the MLR-model than possible because capacity is exceeded. This is the case for the four-way priority intersection, three-way alternative intersection and main road segment. This has been incorporated in Table 8.2 as well, indicated by “N/A” if capacity is exceeded. It effectively shows that certain service levels (’E” and/or “D” in this case) can not be achieved under these circumstances, since the MLR model estimated boundaries that are beyond the predetermined capacity for that particular traffic composition and infrastructure component. This issue occurs more frequently at intersections with capacity constraints (measured in vehicles per hour), whereas four-way roundabouts and three-way priority intersections do not experience this phenomenon.

While it may seem unusual that certain delay levels cannot be achieved, this phenomenon can be explained. The MLR models estimate based on data points generated by the VISSIM models. However, the LoS boundaries are defined in the HCM [58], leading to a discrepancy between the two models. Theoretically, the MLR models can exceed the calculated capacity, allowing delay values to approach infinity. The capacity constraint ensures that the capacity is bounded, which also limits the delay. This implies that certain LoS delay boundaries, as defined in the HCM, can exceed the capacity limit. This outcome is more favourable than having LoS boundaries (expressed in PCU per hour) above the capacity, since this is physically not possible.

The determination for the LoS based on Table 8.2, where four different compositions are tested, is fairly complex due to its distinction between different traffic compositions. It is thus far unable to make estimations for traffic mixes different than the four included in this analysis. Since one of the main goals of this research is to have a widely applicable method for determining the performance of service roads, it is desirable to provide an overview that can be used for other traffic compositions as well. Since the representative compositions (“Base case”, “Equal” and “Inverted”) show similar results, the average of these boundary-values have been taken to capture the LoS determination into one single metric for each infrastructure components. This results into Table 8.3. In the network-model (Chapter 9), the accuracy of these boundaries are tested, which validates if this table can be generalised to other traffic compositions.

From this analysis, the exponential relationship between PCU and the delay is clearly recognised. For example, LoS “B” at four-way priority intersections has a interval length of 109 PCU per hour according

Table 8.3: Level of Service boundaries (PCU/hour) all infrastructure components, combined traffic compositions

LoS	4-way prio.	4-way round.	3-way prio.	3-way alt.	Main road
A	< 1305	< 991	< 1114	< 1054	< 1110
B	1305 - 1414	991 - 1087	1114 - 1212	1054 - 1154	1110 - 1239
C	1414 - 1561	1087 - 1216	1212 - 1340	1154 - 1285	1239 - 1357 (CAP)
D	1561 - 1662	1216 - 1307	1340 - 1430	1285 - 1328 (CAP)	N/A
E	1662 - 1776	1307 - 1409	1430 - 1531	N/A	N/A
F	> 1776	> 1409	> 1531	> 1328 (CAP)	> 1357 (CAP)

to the MLR model, which is translated to 10-15 seconds of intersection delay. Conversely, LoS "E", which has 35-50 seconds of intersection delay, has approximately the same interval length according to the MLR model (114 PCU per hour), while the delay interval is three times as long (15 seconds instead of 5 seconds).

Furthermore, inserting the results of the capacity analysis reveals that certain infrastructure components reach capacity when the delay is less than the highest delay boundary at LoS "F". This is the case at the three-way alternative intersection and main road segments. What this effectively means is that the delay corresponding with service level "E" (and also "D" for main road segments) cannot be achieved, because the components have reached the pre-determined capacity. This is the additional criterium that the HCM has described [58]. In other words, this criterium ensures that the volume in PCU per hour corresponding with the estimated delay from the MLR model does not surpass the maximum measured throughput.

8.3. Application of LoS Boundaries in service road traffic analysis

Table 8.3 results into an overview presenting the boundaries expressed in terms of PCU per hour for each service level and infrastructure component. This can then be used by airport planners and operators to estimate the qualitative performance based on traffic counts at intersections. When analysing traffic counts, it is important to differentiate between the various types of vehicles. The traffic counts can then be put in the MLR model to estimate the total, platoon and forthcoming intersection delay. Based on the intersection delay, an estimation of the performance expressed in LoS can be made, using the combined LoS boundaries presented in this chapter.

An advantage of this methodology is that it is easy to use. Simple calculations can be repeated based on the regression coefficients and subsequent PCU values found in this research, and do not has to be repeated for each airport environment. Furthermore, the PCU values are integrated into the LoS boundaries, creating a comprehensive performance methodology that underlies the assessment procedure.

Additionally, since this methodology uses a passenger car as a standardised reference, other service vehicles not included in this research can be estimated if necessary. Future developments - such as the electrification of the service vehicle fleet - might lead to substantial changes in vehicle parameters [56], and therefore also impact the PCU values of those vehicles. There are various methodologies available for estimating PCU values [52], ranging from simpler to highly complex approaches. The use of MLR - as demonstrated in this research - is however still recommended, as this has proven to capture traffic heterogeneity effectively. If a different method is chosen, calibration with the PCU values found in this research is needed, particularly between the different infrastructure components. Nonetheless, the PCU-capacities and LoS boundaries still remain useful, as they are capable to incorporate other vehicle types as long as these are standardised with a PCU.

8.4. Chapter conclusion: Level of Service boundaries of infrastructure components

To obtain the performance of any service road infrastructure component using a LoS scale, it is important to know the boundary values expressed in PCU per hour between different service levels (A-F), which formulates an answer to research question 1(d). These boundaries can then be used by airport planners and operators to estimate the LoS based on current traffic volumes effectively. The analysis has shown that the boundaries vary slightly under different traffic compositions. This was again - similar to the capacity analysis in Chapter 7 - expected, as PCU values are not captured perfectly in any circumstance. However, the deviation in terms of PCU per hour is small for the representative traffic compositions ('Base Case", "Equal" and "Inverted"), with a largest boundary difference of 10.26%.

A combined LoS boundary framework was presented in Table 8.3, which can effectively be used by airport planners and operators. This table has generalised the outcomes of three representative traffic compositions tested in this analysis, which allows for application to other airports with unique traffic compositions. The framework is effective, easy to use and flexible for future developments of the service road fleet, as well as for the inclusion of service vehicles not covered in this study.

9

Network-level traffic modelling and analysis

This chapter describes the network performance modelling and analysis, which effectively answers research question 2. This research question is interested in upscaling the findings of the component-level analyses to a network-level model. First, the network model input that is implemented into VISSIM is described and explained in Section 9.1. In Section 9.2, the methodology of the determination of the network performance and its execution are explained. Furthermore, the LoS boundaries previously found in this research (Section 8.2) - which can be used to estimate the LoS based on observed PCU flows - is validated by applying it to the network model. Further validation is performed in Section 9.4 by comparing the method proposed in this chapter with an alternative method from the literature. Lastly, a chapter conclusion is given in Section 9.5 based on the findings from the network analyses.

9.1. VISSIM network model input

The first section of the chapter elaborates on the inputs that are used for the network model. It is divided into three parts: The first part explains how the network model is designed, and argues why this model is suitable for network analysis. Secondly, the traffic inputs (compositions, volumes) for all scenarios are presented. Lastly, the simulation settings of the VISSIM network model are explained.

9.1.1. Network model design

In order to analyse the findings from the previous chapter, it is essential that all infrastructure components that are included in the component-level simulation are also represented in the service road system. Additionally, by choosing the right design, the relative performance of the infrastructure components can be monitored. Therefore, it has been decided to construct a fictional roadway system for this research. The four-way priority, four-way roundabout, three-way priority and three-way alternative intersections are implemented and placed strategically to optimise the analysis and to allow for comparison between the intersections. The main road segment is also incorporated into the service road system and serves as a link connecting the infrastructure with aircraft stands.

The main goal of this section is to design a theoretical traffic system which represents the core infrastructure that facilitates traffic movements. However, representing underlying operational mechanisms and strategical placements of airside facilities (baggage handling, fuelling systems, etc.) is not a focus of this analysis, since this research is merely interested in traffic performance in a general sense.

The layout of the terminal building is an important factor for the design of the service road system. In aviation, several concepts exist for the terminal building layout, which have been elaborated in Section 4.3. Choosing between these layouts, it is important that each of the infrastructure components can be represented and analysed effectively, without creating a too large network. This would increase computational complexity and simulation times significantly. Conversely, the network itself should maintain a certain level of complexity, in order to incorporate network effects into the model.

Subsequently, it has been decided to design a “Pier” concept terminal. The design is presented in Figure 9.1. It is important to note that the model represents a section of a larger airport service road network, meaning that vehicles can also enter this network without originating from or destined for aircraft stands inside this model. By creating two identical piers, it allows the model to incorporate a service road layout for pier A and pier B. If the service road of pier B is a mirror of pier A, it allows for a direct comparison between different infrastructure components. In this manner, the network-performance of a four-way roundabout can directly be compared with a four-way priority intersection, as well as a three-way priority intersection with a three-way alternative intersection. The exact characterisation of each individual intersection has been presented in Figure 9.2. In this figure, the mirrored configuration is clearly evident.

The priority rules for each intersection are presented in Figure A.2 (Appendix A). For the four-way priority intersections, priority is given to the main road direction (East to West and vice versa). The priority given on three-way intersections is dependent on the type of intersection. For the three-way alternative intersections on the far end of the main roads (which are the roads where the aircraft stands are connected to), priority is given to traffic from the main road. For three-way priority intersections, vehicles from the main road have to give priority to the other directions.

Aircraft stands are positioned on both sides of piers A and B. These are again mirrored. Within terminal design, it is common practise to place narrow-body aircraft stands on the inside between the piers. This is spatially more efficient, since narrow-body aircraft have a smaller wingspan. Having smaller aircraft on the inside of both piers leads to less area needed for the stand itself, but also the required width of a taxi lane, which is indicated by the yellow line in Figure 9.1. This ultimately reduces the distance between pier A and B, which is an advantage for passengers as well as for the operational performance of airports.

For the model, both piers have 8 narrow-body aircraft stands and 6 wide-body stands, adding up to 28 stands in total. The width of the stands have been based on airport design standard formulated by the ICAO [32]. Narrow-body stands, characterised by code “C” based on the maximum wingspan of these aircraft types, have a width of 36 meter. Additionally, a 4 meter distance between stands has been incorporated, which is to reserve distance around the aircraft for passenger, operator and vehicle movements. Similarly, ICAO characterises wide-body aircraft with code “E”, which needs a stand width of 65 meter. Incorporating a reserve distance of 5 meter results into a distance of 70 meter between wide-body stands.

To make an indication of the size this airport sub-part represents, an estimation of the yearly passengers that is typically transported on such airport is made. For this calculation, the typical peak hour passengers (TPHP) [59] is used, which can estimate the highest hourly passenger flow on an average day based on the yearly number of passengers. Conversely, if an approximation of the hourly passenger flow during peak hour is known, the total number of annual passengers can be estimated using TPHP. Considering 16 narrow-body aircraft movements (departure or arrival) with 140 passengers on board (average of Figure 5.2a, Box and Whisker plot number of passengers for narrow-body aircraft), and 12 wide-body movements with 292 passengers on board (Figure 5.2b, Box and Whisker plot number of passengers for for wide-body aircraft), this results into an approximate highest hourly passenger flow of 6.000 passengers. This is not taking into consideration limitations to other airside facilities such as runway capacity. According to TPHP [59], the sub-part of the airport that is designed for this research typically facilitates 12 to 15 million passengers per year. It is noted that this is lower than the size of airports that this research is focussing on (20+ million passengers per year), but it is important to consider that the traffic model is a representation of a fraction of a larger airport. Additionally, having a network twice the size of the one created does not necessarily mean that the roads are twice as congested or saturated, since the demand is generally more spread out across a larger network. The created network therefore holds sufficient level of complexity, facilitates a reasonable amount of passengers during peak hour and includes the different infrastructure components analysed before.

9.1.2. Traffic input

The “Base Case” traffic composition of the component-level analysis, which has been formulated and explained in Section 5.1 (Vehicle composition estimation), has been chosen for all simulations in this analysis. This also includes the use of buses, which are not necessary for contact stands. However,

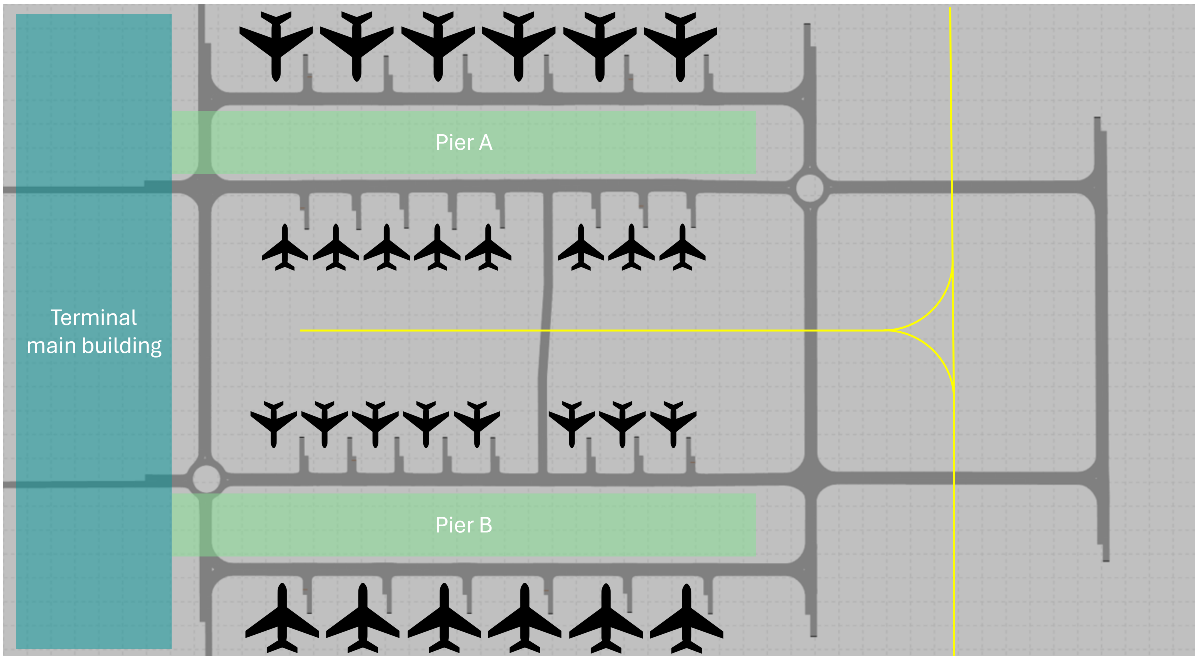


Figure 9.1: Service road design network model, including terminal lay-out

since this can also represent a part of a larger airport, it is possible that buses are also present at an airport as this one. Passenger cars however, which had been included in the component-level analysis to represent a reference for the PCU-analysis, have been excluded from the "Base Case" traffic composition for the network-level analysis. In this way, only actual service vehicles are represented. In the reference case for this analysis, the traffic volume across the network is set up to represent a typical peak hour of an airport. Analyses of the HCM [58] are typically conducted during peak hour conditions, as these periods represent the most challenging operational scenarios, thereby offering a critical assessment of the infrastructure's performance.

In this case, it is assumed that one aircraft needs servicing per aircraft stand during a one-hour period. In this manner, the number of vehicles needed per aircraft stand can be derived from Figure 5.1, which describes the number of vehicles needed per aircraft and stand type. Therefore, narrow-body aircraft stands have 12 service vehicles in this model, while wide-body stands have 19. This accumulates to 420 vehicles departing across all gates. This means that also 420 vehicles need to be generated that provide service to the aircraft (arrival at gates). The generation of these vehicles are spread out across the remaining input-links of the network. In addition to the origin-destination traffic, a 15% miscellaneous traffic input has been included to account for traffic movements not directly related to servicing aircraft or traffic not destined inside this area (through-traffic). In total, the model stochastically generates 900 vehicles per hour into the network.

To represent service roads traffic more realistically, traffic around the terminal building is more dense than on service roads on the outer sides of the network (Eastward in Figure 9.2). This is because many important facilities, such as baggage handling, passenger transport and cleaning facilities are typically situated inside or near the terminal building. Therefore, the West-side of the modelled network is subjected to heavier traffic volumes, resulting in larger delays.

To draw conclusions that are broadly applicable to airports, it is crucial to test the model under conditions of increased traffic volume. While the traffic at the fictional airport is representative, the volumes and roadway designs vary from one airport to another. Therefore, this network analysis is conducted across multiple scenarios, with traffic volumes incrementally increased in each scenario. Specifically, in each scenario, all traffic inputs shown in Figure 9.2 are increased by 25%. This approach results in the set-up presented in Table 9.1. "Narrow-body" and "Wide-body" refers to the inputs at the associated aircraft stands. "Terminal side" refers to the input on the West-side of the main road segments, while "Outer side" are all inputs East-side of the main road segments.

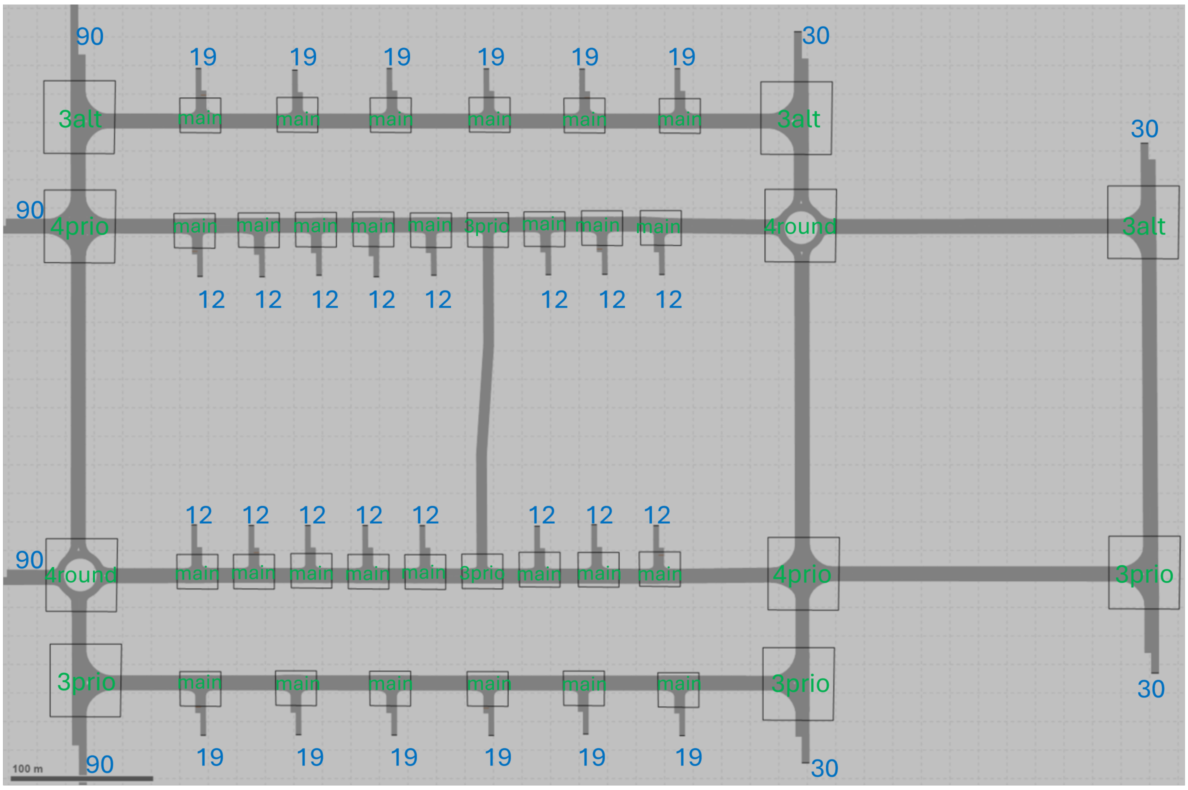


Figure 9.2: Network model including infrastructure components (green) and traffic input volumes (blue) for basic peak conditions (Reference scenario)

Table 9.1: Vehicle volumes for each scenario of network analysis

Scenario	**Volume (veh/hour)**				
	Total	Narrow-body	Wide-body	Terminal side	Outer side
Reference	900.0	12.0	19.0	90.0	30.0
Reference +25%	1125.0	15.0	23.8	112.5	37.5
Reference +50%	1350.0	18.0	28.5	135.0	45.0
Reference +75%	1575.0	21.0	33.3	157.5	52.5
Reference +100%	1800.0	24.0	38.0	180.0	60.0

9.1.3. Simulation settings

The VISSIM model is simulated ten times to ensure reliable results and to account for the stochastic nature of the model. A warm-up period of 5 minutes is chosen to let the vehicles occupy the model, which is the time a slow vehicle (15 km/h) approximately takes to get from one side of the model to the other. A data-collection period of 60 minutes follows, resulting into a total simulation-time of 1 hour and 5 minutes.

The data-collection period is divided into 5-minute time intervals. These shorter intervals enable the collection of more detailed, microscopic-level data, as opposed to analysing aggregate data over the entire simulation run. Due to the stochastic generation and distribution of vehicles, the condition of a particular intersection could vary significantly from one 5-minute interval to the next. It allows to capture events that occur during a interval more effectively. Additionally, if the simulation period used to determine the LoS is too long, it often results in an intersection appearing to perform well. However, in reality, traffic accumulation within the network can cause many vehicles to experience much longer delays than what the hourly-based LoS would suggest. This phenomenon should be considered when determining the LoS of the network and is incorporated efficiently by dividing the simulation into 5 minute time intervals.

Within VISSIM, node evaluation is enabled to capture the number of vehicles of each type to enter any node during each interval period. This information is needed to predict the intersection delay and the subsequent LoS. All nodes in the network model are illustrated by black boxes in Figure 9.2. Additionally, network vehicle performance evaluation is enabled in the network model to analyse the performance of the vehicles across the different scenarios. This is important to compare the results from the LoS analysis within this research with a different method for determining the LoS, also based on the HCM [58].

9.2. Network Level of Service determination

9.2.1. Analysis approach

This section describes how the LoS is determined across an entire network, therefore formulating an answer to sub-research question 2(a), which aims to identify an appropriate methodology for evaluating the performance of an entire service road network. The chosen method is then applied in the network-analysis to determine the performance of the network, which ultimately draws conclusions on sub-research question 2(c). This research question focuses on the performance of a representative service road network.

The HCM considers Percent Free Flow Speed (PFFS) as the main criteria for determining the LoS of urban roadway networks, also called facilities by the Transportation Research Board [58]. PFFS is calculated by dividing the average travel speed by the free flow speed and then multiplying the result by 100 to express it as a percentage. An advantage of this method is that it captures roadway user perception by reflecting travel time and delay across multiple consecutive intersections that the user passes through. Video-based data collection of Indian urban roads and subsequent LoS-analysis based on PFFS [46] has confirmed that the users perception can indeed be predicted by the average travel speed. The HCM considers the travel time of through-traffic, which in urban settings takes up a considerable amount of the traffic present. Through traffic in roadway networks refers to vehicles that pass through an area without stopping at local destinations.

However, a disadvantage of applying this method to airport service roads is that most traffic is destined for various points within the roadway network, rather than simply entering on one side and exiting on the other. In airport environments, it would be highly complex to set up the sections for which the travel time is measured, since there are many origin-destination combinations and none of them generally dominate the total traffic flow.

Additionally, compared to traditional urban roadway users, the traffic on airports is much more heterogeneous. While some variation in travel speeds may exist between light and heavy vehicles on urban roadway systems, most vehicles are generally capable of achieving the maximum travel speed. Airport service road users on the other hand, have various vehicle types that do not travel the speed limit, and also have significant various acceleration and deceleration profiles (see Table 5.2). This would make the determination of PFFS even more difficult, since there is not one but multiple free flow travel times for each vehicle profile.

The two arguments given would lead to overly complex and expensive data collection on service roads, which can discourage airports into analysing the performance of their network. Therefore, simpler methods need to be explored for airport service roads specifically. Because of the complexity caused by destination-based traffic and traffic heterogeneity, it supports the case for choosing a network-analysis method that decomposes the network into smaller segments or intersections. This then effectively replicates the LoS-method of the component-level modelling part of this research, by gathering this information for each individual component. This method is less complex, as it assesses the performance of networks by basic vehicle counts on each intersection. Furthermore, this method allows for a microscopic view of the network, as it is able to evaluate individual bottlenecks. However, the findings of each individual component still needs to be transformed into a LoS for the entire network.

The LoS of an entire network is determined in this research as follows: For each time interval of 5 minutes, the LoS of every infrastructure component is determined based on the previously established MLR models that were used to determine the PCU values (see Chapter 6 for the MLR models). Note that the volume-levels for each 5 minute interval is transformed into an hourly flow, split between the different types of vehicles. For the network model, this ultimately results into 12 different LoS values per data-collection period of one hour, for each intersection or node analysed. The number of vehicles that are exposed to this LoS are then counted for each time interval. This ensures that the LoS is corrected for traffic volumes. This is necessary because more vehicles (users) experience LoS “D” in a single time interval compared to vehicles that experience LoS “A”, because the degradation of service level is caused by the presence of additional vehicles themselves.

By collecting the data for each intersection and time interval, the total counts of vehicles experiencing a certain LoS can be collected, indifferent to which intersection type it is. This leads to an overview of how many many vehicles have experienced a LoS A, B, C, D, E or F. In this manner, the spatial (intersections), temporal (time intervals) and volume (vehicles) factors are taken into consideration when determining the LoS of an entire network.

Subsequently, the weight of each intersection is dependent on the flow that each node (or intersection) facilitates. Main roads however, consist of multiple adjacent nodes, the number being dependent on the number of aircraft stands. It is argued that this can lead to unrepresentative LoS determinations of entire networks, as main roads with 8 stands then have 8 times more relative weight than any other type of intersection in the network. It has therefore been decided to capture the LoS of all aircraft stands into a single measurement for the entire main road segment. The LoS of a main road is determined by the worst-performing aircraft stand in terms of LoS. If for example a main road has 7 aircraft stands with LoS “A” and 1 with LoS “B”, the main road has a LoS “B”. Reasoning for choosing this method is that main roads are effectively closely positioned intersections, with each intersection having an effect on the performance of an aircraft stand or intersection downstream and upstream.

Next, the LoS counts need to be transformed into a single measure for the entire network. This is done using different cut-off percentiles. The optimal cut-off percentile can vary between airports, depending on their specific performance requirements for service roads. Therefore, it has been decided to test the LoS determinations with different cut-off percentiles, which are 95, 98, 99 and 100%. The cumulative percentage for each scenario is then determining for the LoS of the network. Using different cut-off percentiles allows for flexibility in meeting the unique performance requirements of various airports. This approach also facilitates a sensitivity analysis, helping to identify the most appropriate threshold for optimal performance. [33]

Expected results

The analysis is expected to obtain reliable results by aggregating the data for each intersection, time interval and vehicle. The “Reference”-scenario, which represents typical peak hour conditions, is expected to perform (sub-)optimal (LoS “B” or better) across all measurements. This expectation arises from the fact that most airports have minimal concern regarding the performance of service road traffic [49], with issues primarily occurring at very large airports [15]. Therefore, some significant drops of LoS (“D” or worse) is expected when the traffic volumes is is increased by 50% at the 100th percentile, while on the 95th percentile the performance is expected to be (sub-)optimal still. The network is expected to experience heavy delays when the traffic is increased by 100%, with major drops of performance (“E” or “F”) during certain time intervals. It is also expected that, based on the performance comparison in Chapter 8 (LoS determination of infrastructure components), four-way priority intersections are subjected most to performance drops.

9.2.2. Results

This section reports the results from LoS analysis for the entire airport service road network that is designed in this chapter. First, the results of all scenarios are presented (Table 9.2), including the number of vehicles that experienced each LoS across the duration of the simulation, for all ten simulations. This is then transformed into a percentage for the entire scenario. Lastly, the cumulative percentage indicates what percentage belongs to that LoS or better. This is needed to obtain the performance divided between the percentiles, which is reported in Table 9.3.

Table 9.2: Statistics network-level LoS determination, all scenarios

Count						
Scenario	A	B	C	D	E	F
Reference	24275	0	0	0	0	0
Reference +25%	30184	0	89	0	0	0
Reference +50%	35876	501	189	0	0	0
Reference +75%	39290	1278	465	106	51	61
Reference +100%	38411	2079	1656	303	432	62
Percentage						
Scenario	A	B	C	D	E	F
Reference	100.00%	0.00%	0.00%	0.00%	0.00%	0.00%
Reference +25%	99.71%	0.00%	0.29%	0.00%	0.00%	0.00%
Reference +50%	98.11%	1.37%	0.52%	0.00%	0.00%	0.00%
Reference +75%	95.25%	3.10%	1.13%	0.26%	0.12%	0.15%
Reference +100%	89.45%	4.84%	3.86%	0.71%	1.01%	0.14%
Cumulative						
Scenario	A	B	C	D	E	F
Reference	100.00%	100.00%	100.00%	100.00%	100.00%	100.00%
Reference +25%	99.71%	99.71%	100.00%	100.00%	100.00%	100.00%
Reference +50%	98.11%	99.48%	100.00%	100.00%	100.00%	100.00%
Reference +75%	95.25%	98.34%	99.47%	99.73%	99.85%	100.00%
Reference +100%	89.45%	94.29%	98.14%	98.85%	99.86%	100.00%

From Table 9.2, the results show that in the reference scenario, the LoS based on the criteria of the HCM is always "A". This means that for every node during all time intervals, the predicted delay is less than 10 seconds for four-way intersections, 8 seconds for three-way intersections and 5 seconds for main road stands. To create context for this outcome: For this scenario, on average 1 vehicle is generated somewhere into the network every 4 seconds, given the total hourly volume of 900 vehicles per hour. The size of the network and the distribution of traffic are sufficient to facilitate this hourly flow, which is also as expected. The results confirm this expectation.

In Appendix C, an overview is presented that reports the vehicle counts recorded across different intersection types, from which conclusions can be drawn regarding the relative performance of intersection types. The network is starting to show deterioration at numerous time intervals for certain intersections for scenarios where the total input volume is increased by 25% and 50%. Looking at the intersections that are subjected to this deterioration (Table C.1 in Appendix C), 17 out of 18 time intervals that are LoS "B" or worse belong to intersection type four-way priority, while the single remaining time interval with LoS "B" belongs to a four-way roundabout intersection. This results was also expected, since this infrastructure component also performed relatively poor in prior analyses within this research. Three-way intersections as well as main road stands still perform optimally and are assigned LoS "A" in all cases for up to 50% increase of traffic volume.

The deterioration of the network becomes more noticeable from scenario "Reference +75%". In more instances (2.26%), the service level of intersections drops to "B" or worse, representing 4.75% of all vehicles. In this scenario, LoS "E" and "F" are both observed once at intersections, which in both cases happened at a four-way priority intersection. The first drop of LoS is observed for a three-way intersection in this scenario, which happened at a three-way priority intersection.

Lastly, the busiest scenario shows severe service drops (LoS "D" or worse) in 15 time intervals, all of them belonging to a four-way priority intersection. The network is struggling to maintain LoS "A" more frequently, with 4.96% of the all time intervals a LoS of "B" or worse is reported. This accounted for 10.55% of the vehicles. Interestingly, 60.94% of the vehicles experiencing LoS "B" was on four-way priority intersections, 22.66% on four-way roundabouts, 5.63% on three-way priority intersections and 10.77% on three-way alternative intersections. None of the main road segments recorded a LoS drop in all scenarios.

Table 9.3: Percentiles of network-level LoS determination, all scenarios

Scenario	95%	98%	99%	100%
Reference	A	A	A	A
Reference +25%	A	A	A	C
Reference +50%	A	A	B	C
Reference +75%	A	B	C	F
Reference +100%	C	C	E	F

Table 9.3 shows that even in the most critical assessment (100th percentile) of the performance of the service road network, the reference scenario still maintains optimal state over all its intersections. Conversely, LoS remains “A” for all input volumes up to 75% increase of the reference scenario for the 95th percentile. If the input volume is increased further to 100%, the 95th percentile indicates a LoS “C”, which is still considered an acceptable level of delay according to the HCM [58]. At the 98th percentile, optimal LoS is still maintained for input values 50% increase of the reference volume, but at 75% the performance drops slightly to LoS “B”. This trend continues into the 99th percentile, with LoS “A” being realised up and until the reference volume is increased by 25% of the reference volume. Interestingly, the network shows signs of severe deterioration at 100% increase of the reference volume, as a LoS decreases to “E” for the 99th percentile. Lastly, at the 100th percentile, the severe drops of service are noticeable at 75% increase of the reference volume already, even dropping to LoS “F”. This aligns with the expected results, although severe drops occur at a 75% increase in traffic volumes rather than at 100%. Volume levels 125% and 150% have decreased performance at the 100th percentile, but are still within reasonable performance limits (LoS “C”).

This analysis has demonstrated that the network performance based on the proposed methodology is promising under peak hour conditions. At every five-minute interval, the network remains in an optimal state, which is a positive indicator for the overall condition of airport service roads. However, generalisations for other airports should be made with caution, as performance is always dependent on the network design and volume levels. For instance, a similarly designed network might have a critical baggage handling facility centrally located within the terminal building, potentially causing stress at connected intersections. Therefore, it is essential to conduct LoS analysis across various airport environments before drawing conclusions about the overall condition of airport service roads.

Additionally, the stress on service road components can potentially increase in the future. Enhanced operational efficiency of airside facilities might require more service vehicles, which increases the need for network performance studies. Other future developments, such as the electrification of service vehicles [56], can also have a direct impact on the number of service vehicles required to facilitate aircraft turnarounds. This analysis has shown that the service road network designed in this research is robust enough to facilitate up to 50% more traffic compared to basic peak hour conditions without causing substantial network performance drops.

9.3. Level of Service boundary validation

9.3.1. Analysis approach

This section outlines the process for answering research sub-question 2(b). This part of the research aims to determine whether the boundaries identified and presented in Table 8.3 are applicable to service road networks in general. This table facilitates a simplified estimation of the performance of infrastructure components based on PCU volumes.

Since the method to determine the LoS of an entire network that is proposed depends on the LoS of each individual infrastructure component, it is important to validate that the LoS boundaries make an accurate indication to which service level an intersection belongs to in the network-model. Since the boundary-values are based on pre-determined traffic compositions (“Base Case”, “Equal” and “Inverted”), it is yet unknown if the boundaries are sufficiently robust to generalise the findings for any given traffic composition. While the network analysis uses the “Base Case” traffic composition at each network entry, stochastic processes such as turning rates and vehicle inputs significantly impact the network-level model. As a result, the observed vehicle composition at intersections can deviate considerably from the “Base Case” composition within any random 5-minute interval.

The intersection delay for every node in the network is modelled using the MLR models presented in Chapter 6 (PCU analysis). It is therefore not necessary true that a certain traffic volume in terms of PCU per hour will always result into the same delay, therefore not exactly the same LoS. The following example explains this phenomenon more clearly: Consider two (unrealistic) situations for a four-way priority intersection. In the first one, exclusively 200 baggage trains are recorded, which in accordance to the PCU-values of this intersection type is equivalent to 700 PCU per hour. In the second situation, exclusively 300 buses are recorded, which is also approximately 700 PCU per hour. According to Table 8.3, this would result into two intersections with LoS “A”. However, following the MLR models (regression coefficients are reported in Appendix B), the first situation leads to a delay per vehicle of 10.1 seconds, which is characterised as LoS “B”. The second situation leads to a delay per vehicle of 6.7 seconds, which is LoS “A”. This means that the PCU boundaries previously presented are not accurate under all circumstances, highlighting the importance to study their accuracy further.

This difference can be explained by the fact that Table 8.3, which estimated the LoS based on PCU flows, is a simplified version of the estimation using the MLR models. The MLR models assume a delay per vehicle as the total delay divided by the total number of vehicles. While the total delay with 700 PCU each is equal, the number of vehicles (200 baggage trains vs. 300 buses) is not equal. Furthermore, the platoon delay, which is calculated separately, can generate significantly different values for the same PCU flow. This is because the PCU values are not derived from the platoon delay simulations, but from the intersection simulations. Therefore, each vehicle type has a different impact on platoon delay that is not exactly proportional with the total delay, therefore generating different results. Platoon delay and delay composition has been explained in Chapter 8, Section 8.1.1. The simplified version using PCU boundaries is however more usable, effective and easier to interpret for airport operators or planners, without needing complex statistical analyses for future or existing airports.

The results of this analysis therefore show in how many cases the predicted LoS using MLR corresponds with the LoS that is indicated in terms of PCU per hour in Table 8.3. This analysis has been performed using the “Reference +100%” scenario input, as this produced the most dense traffic and therefore the largest variation in service levels, which was found in Section 9.2 (Network LoS determination). This analysis is essential to prove the robustness of predicting the LoS based on PCU per hour. Additionally, it also indicates whether the LoS determination is insensitive to vehicle compositions other than “Base Case”, “Equal” and “Inverted”. This is a crucial step, as vehicle compositions vary between airports, therefore limiting the applicability to other airport if the LoS is too sensitive and the resulting LoS determinations are inaccurate.

Expected results

This analysis is expected to prove that the LoS boundaries are accurate and therefore valid to use for future airport service road traffic performance studies. However, the accuracy of the LoS boundaries is not expected to be perfect (100%) since the methodology for the LoS boundaries is simplified using the MLR models. It is expected that inaccurate LoS estimations are not caused by the typology of the intersection.

9.3.2. Results

This section presents the analysis as described in Section 9.3.1. It first presents an overview of the observed vehicle compositions, which highlights the importance of this analysis. The validation results of the LoS boundaries are reported afterwards. The observed results are discussed afterwards.

Table 9.4 is presented to illustrate the variation of the observed vehicle compositions more clearly, highlighting the importance of this analysis. This table presents the number of vehicles recorded within a 5 minute time interval for a four-way roundabout intersection, for three random consecutive time intervals. These examples show that within a small time interval, the distribution of the vehicle composition can vary significantly. For each time interval and node, the vehicle counts are recorded, resulting into 4800 unique traffic compositions. Averaged out, the distribution of vehicles is similar to the “Base Case” composition that is calculated in VISSIM model input chapter (Chapter 5, Figure 5.3). However, a proper deviation is illustrated, indicating that the number of vehicles of each type can vary significantly for any random vehicle composition during a given time interval. This highlights the importance of testing the sensitivity and robustness of the framework presented on a network-level, as the LoS boundaries are previously only tested with fixed traffic compositions. These were called “Base case”, “Equal”, “Inverted” and “Passenger car only”, and were also described in the capacity analysis and LoS determination, Chapters 7 and 8 respectively.

Table 9.4: Example vehicle composition variation, random three consecutive time intervals, four-way roundabout

Sample	Bus	Cater.	Fuel	Clean	Water	Bags	Cargo	Push	Belt	High
1	3	3	4	7	3	6	1	0	2	0
2	1	6	1	1	5	3	0	2	0	1
3	0	9	1	3	6	5	3	0	1	0

In Table 9.5, a summary of the results of the boundary validation analysis are given for the “Reference +100%” scenario. This input is chosen for this analysis because this scenario shows the largest variation in LoS levels, and this is particularly interesting for this analysis because it searches for mismatches of LoS between the MLR model and the PCU boundaries.

The results are presented for two different cases: all nodes and all nodes excluding main road nodes. The reason this distinction is made is because, as explained previously in Section 9.2.2, the main road nodes perform to the standard of LoS “A” in any of the conditions that are simulated. The results show that the cases in which a difference between the predicted LoS based on the MLR and based on the PCU boundaries have volume levels of approximately 1000 PCU per hour minimum. The highest observed flow rate at any aircraft stand (main road infrastructure component) during one single interval period is 950 PCU per hour, while the average is only 450 PCU per hour. For this reason, it has been decided to interpret the results also without the main road nodes. The column “Inside boundaries?” represent whether or not the PCU per hour observed and the associated LoS for that case fall inside the boundaries in terms of PCU per hour. If this is not the case, this case is called a mismatch.

Table 9.5: Results LoS boundary validation, All nodes and excluding main road nodes, Reference +100% scenario

	All nodes		**Excl. Main Road**	
Inside boundaries?	Counts	Percentage	Counts	Percentage
Yes	4601	99.3%	1361	97.8%
No	31	0.7%	31	2.2%

Table 9.5 show that of 4632 cases selected, which are all cases that have an observed traffic flow, only 0.7% of the cases have a mismatch of the LoS determination. This is across all nodes, including main road segments. By excluding these, the results show that the share of mismatches increases to 2.2%. This overview also indicates that all mismatches do indeed come from the intersections (four-way priority, four-way roundabout, three-way priority and three-way alternative) and not from the main roads, as the count of mismatches is 31 in both cases. A 97.8% accuracy is observed for this traffic intense scenario, indicating that LoS can be predicted adequately based on PCU per hour boundaries from Table 8.3. This suggests that the LoS boundaries are robust and therefore applicable to various airport environments, creating an effective and accurate estimation method.

In Appendix C.2, the statistics for the 31 mismatches are reported. The average difference is 23.3 PCU per hour, with a maximum difference of 97.0 PCU per hour and a standard deviation of 23.1 PCU per hour. Mismatches are observed across all intersection types - which aligns with the expected results - though four-way intersections are more frequently represented. This is likely due to their strategic positioning within the network, particularly on the West-side, where they serve as critical bottlenecks. Consequently, these intersections experience higher average traffic volumes (both in vehicles per hour and PCU per hour), increasing the likelihood of mismatches. Notably, mismatches are exclusively observed at volume levels exceeding 985 PCU per hour. From this it can be concluded that mismatches occur more frequently at relatively higher PCU flows, although the occurrence and impact of a mismatch remain limited.

9.4. Validation of network Level of Service methodology

In this section, the results presented in previous Section 9.2.2, in which the LoS of the network-model is determined based on the approach proposed in this research, are validated by extracting a different output indicators from VISSIM. This output indicator is average travel speed, and is needed for the LoS determination based on roadway facilities (networks) of the HCM [58]. In this analysis, a comparison is made between the different service levels resulting from the method of HCM and the component-based method described in this research. This section in itself does not answer a specific research (sub-)question, but is important to validate if the methodology for determining the network-performance is accurate.

An indication is given of the average travel speed calculated by the VISSIM simulation model. The average travel speed is obtained for every vehicle recorded in each scenario. The Percentage of Free Flow Speed (PFFS) is calculated by dividing the average travel speed by the FFS. The FFS is determined through the individual speed profiles for each vehicle type, corrected for the average share in the "Base Case" traffic composition. The resulting LoS of the network using the criteria of the HCM based on the PFFS [58] is presented in this section. The results from both methods of LoS determinations are compared and interpreted, despite the large methodological differences. The findings are presented in Table 9.6. These findings are compared with Table 9.3, which reported the LoS for different cut-off percentiles.

Table 9.6: Average travel speed and Level of Service determination based on Percentage of Free Flow Speed [58]

Scenario	Avg. travel speed (km/h)	PFFS	LoS (PFFS)
Reference	16.08	69.1%	B
Reference +25%	15.52	66.7%	B
Reference +50%	14.75	63.4%	C
Reference +75%	12.91	55.5%	C
Reference +100%	9.92	42.6%	D

From this table, it can be concluded that the LoS determination differs slightly from the component-level method provided in this research. The most notable difference is the LoS at the reference scenario. According to Table 9.3, this is supposed to be LoS "A" for all percentiles, while it is LoS "B" in this calculation. This difference can be explained by three reasons.

First, the LoS determination based on intersections is corrected for platoon delay occurring at intersections and is focussed on intersection delay. Therefore, the platoon delay seemingly makes the network perform worse. It is however still a form of delay, so it does say something about the performance of a network. The LoS determination method in this research only focuses on pure intersection delay.

Additionally and more importantly, the PFFS criteria set up by the HCM [58] is calibrated for urban roadway settings. As mentioned before, these networks are much less subjected to traffic heterogeneity, so platoon delays occur significantly less compared to service roads. The boundary for LoS "A" for example is therefore met sooner, as faster vehicles (speed profile 30 km/h) are stuck behind slower vehicles (speed profile 25 or 15 km/h). If the PFFS-based method would be applied to service roads, the boundaries need recalibration for service roads specifically because the state of traffic is substantially different for identical values of PFFS.

Lastly, the LoS of a network based on PFFS is calculated for through traffic. As explained in Section 9.2.1, traffic in service road networks are much more destination-based. This can also affect the traffic performance of the network, as routing options are more limited if a vehicle has to be at a certain point inside the network. This hypothesis is outside the scope of this research and has therefore not been studied further, but it is hypothesised that this can indeed impact the traffic state of the service road network. If that is the case, additional calibration is needed for the LoS criteria.

9.5. Chapter conclusion

This section presents a preliminary conclusion based on the findings reported in this chapter. It also formulates an answer to sub-research questions 2(a) (expression Level of Service of service road network) 2(b) (applicability Level of Service boundaries) and 2(c) (evaluation performance network-level model). The conclusions drawn in this section limits itself to the network-level analysis. An overall conclusion is described in Chapter 10.

9.5.1. Expression Level of Service of service road network

Based on the analysis, the LoS of an entire service road network can be effectively expressed by decomposing the network into smaller segments or intersections and evaluating each component individually. This method addresses the complexity caused by destination-based traffic and traffic heterogeneity, which are significant challenges in airport environments compared to traditional roadway systems.

The actual LoS of the network is determined by counting the number of vehicles (users) that experienced a specific LoS at a certain intersection. By collecting data for each intersection and time interval, and considering the spatial, temporal, and volume factors, a comprehensive overview of the LoS for the entire network can be achieved. The LoS of main roads is determined by the worst-performing aircraft stand, which ensures that the most critical areas are not over-represented. The use of different cut-off percentiles allows for flexibility in meeting specific performance requirements, making this approach adaptable to various airport settings.

This method provides a less complex and more practical solution for determining the LoS of service road networks. It is able to assess the network on a more microscopic view, as bottlenecks can be analysed individually, while their impact on the network are proportionable. This allows for a more comprehensive management strategy, as airports not only understand the overall performance but also how it is negatively impacted by looking at the performance of individual intersections.

9.5.2. Applicability Level of Service boundaries

Based on the method and results presented, the boundaries of different service levels expressed in PCU per hour are largely applicable to service road networks. The analysis shows that the LoS boundaries identified are robust and can accurately predict the service level of intersections within the network model. The validation results indicate a high accuracy rate, with 99.3% of cases falling within the predicted boundaries when including all nodes, and 97.8% when excluding main road nodes.

The method accounts for variations in vehicle compositions and traffic volumes, which demonstrates that the LoS boundaries are not overly sensitive to different traffic compositions. This robustness is crucial for generalising the findings to various airport settings. However, the analysis also highlights that mismatches occur at higher traffic volumes, particularly at critical bottlenecks like four-way intersections. These mismatches, though minimal, suggest that while the boundaries are generally applicable to a large variety of airports, there may be specific scenarios where additional refinement is needed.

Overall, the findings support the applicability of the LoS boundaries to service road networks, providing a reliable framework for evaluating network performance. This approach ensures that airports can effectively assess their service road networks based on individual infrastructure components using Table 8.3, even with varying traffic compositions, volumes and turning rates per small time interval. Table 8.3 estimates the LoS based on PCU values for different infrastructure components.

9.5.3. Evaluation performance network-level model

The representative network designed in this research performs optimally under all reference case input volumes, with no deterioration recorded at any intersection during the simulations. This is a positive sign, as it represents ambitious peak hour conditions with one aircraft either arriving or departing at each stand.

With increased traffic volumes of 25% to 50%, the network shows signs of deterioration, primarily at four-way priority intersections. This highlights the need for careful assessment of these intersections in any network, as increased traffic can lead to significant bottlenecks. In this particular network, the central placement of the four-way priority intersection partially explains its lack of performance during certain time intervals. Conversely, four-way roundabouts positioned similarly in the network show fewer performance drops compared to four-way priority intersections. Even with vehicle inputs doubled, the LoS remains acceptable at the 95th percentile. However, severe drops in service levels are observed, indicating that delays must be accounted for when deploying service vehicles. Failure to do so risks aircraft not being serviced on time, negatively impacting the operational performance of airside environments.

Assessing the network using performance measurements from the HCM [58], based on average travel speed, the network performs nearly optimal (LoS “B”) for input values up to 125% of the reference case and acceptable (LoS “C”) up to 175% of the reference case. With this framework, the network also shows unacceptable (LoS “D”) service levels for double the amount of traffic. Comparison between this measurement and the methodology established in this research highlight minor differences in terms of LoS. This discrepancy is due to factors such as platoon delay and the calibration of PFFS criteria for urban settings, which differ from service road networks.

10
Conclusion & discussion

The conclusion and discussion of this research are described in this chapter. First, the key findings are summarised and contextualised in Section 10.1. Furthermore, the implications for both science and for practice are described in Section 10.2, after which the limitations of the methodology of this research are presented in Section 10.3. Recommendations for future research are made in Section 10.4. A final conclusion is given in Section 10.5, taking into consideration the aforementioned key takeaways.

10.1. Key findings and interpretation

This study on airport service roads for traffic modelling included several key infrastructure components: four-way priority intersections, four-way roundabouts, three-way priority intersections, three-way alternative intersections, and main road segments connected to aprons. These components are frequently found on service road networks, form the backbone of airport roadway networks and were therefore included for further analysis.

First, the component-level analysis confirmed high traffic heterogeneity, with service vehicles displaying distinct speed profiles (15, 25, and 30 km/h) and varying acceleration and deceleration characteristics. PCU values were used to capture these differences, and results showed significant variation across different infrastructure components. Notably, four-way priority intersections exhibited higher PCU values compared to four-way roundabouts, which indicates that roundabouts handle service vehicles more efficiently and are thus less sensitive to traffic heterogeneity. Similarly, both types of three-way intersections showed relatively low PCU values, suggesting that delays are less severe at identical volume levels in terms of vehicles per hour compared to four-way priority intersections. The literature places significant emphasis on comparing methods for determining PCU values and enhancing existing methodologies [2, 8, 13], but little focus has been on finding differences in PCU values between different intersection types. However, this research has shown that for heterogeneous traffic, which is prevalent on service roads, it is essential that PCU values are determined for individual components.

The capacity analysis revealed that while capacity, expressed in PCU per hour, was largely consistent across different traffic compositions, minor variations existed. These variations became particularly notable under more extreme or unrealistic conditions. This suggested that the PCU-based approach provided a reliable estimate for normal operations but did not fully capture all performance factors under certain circumstances.

All conditions being equal, the four-way roundabout intersection performed better compared to a four-way priority intersection, with a capacity difference of 19.9% in terms of vehicles per hour. The three-way priority intersection has 21.1% more capacity than the three-way alternative intersection. The main road with three aircraft stands, which effectively is three closely positioned three-way intersections, has a reduced capacity of 5.6% compared to a singular three-way intersection. This reduced capacity compared too three-way intersections can be explained by the interaction of closely positioned intersections, as downstream bottlenecks have an effect on the traffic flow upstream as well [63].

The component-level LoS analysis established LoS boundaries for different service road infrastructure components, expressed in PCU per hour. The results indicate that LoS boundaries vary depending on traffic composition, though the deviations remain relatively small. These boundaries allow airports to estimate the LoS of individual infrastructure components based on current traffic volumes. Research on comparing methods for determining the LoS of roadways [24] indicates a potential for determining the LoS based on the volume-to-capacity ratio. The boundaries expressed in PCU per hour in this study effectively represent this method, but a more complex and analytical approach is applied to account for traffic heterogeneity. Also, instead of considering a fixed volume-to-capacity ratio for all components, this research has made a distinction for each infrastructure component based on estimated delays from MLR models.

The LoS of airport service road networks can be effectively determined by breaking the network down into smaller infrastructure components and assessing each intersection individually. This method accounts for the complexity caused by destination-based traffic flows and vehicle heterogeneity, both of which significantly impact airside service roads and are difficult to incorporate using traditional methods formulated in the HCM [58]. By evaluating the LoS at each intersection and aggregating the results, a comprehensive understanding of network performance can be obtained. The method ensures that spatial (intersections), temporal (time interval) and flow (vehicles) factors are taken into consideration when determining network LoS. The flexibility of this approach, through the use of different cut-off percentiles, enables airports to tailor their evaluations to meet specific operational requirements. Ultimately, this methodology provides a practical framework for identifying bottlenecks and understanding their proportional impact on the entire network, supporting more effective infrastructure planning and traffic management.

The results further demonstrate that the LoS boundaries established in this research are largely applicable to service road networks, confirming their robustness in predicting service levels across different infrastructure components. Validation efforts indicate that 99.3% of cases fell within the predicted LoS boundaries when all intersections were considered, and 97.8% when excluding main road nodes. This suggests that the method reliably accounts for traffic composition and volume variations without being overly sensitive to minor changes. However, small mismatches were observed, particularly at higher traffic volumes and critical intersections such as four-way priority intersections, where capacity constraints led to minor deviations. These findings confirm that while the LoS boundaries provide a solid foundation for evaluating service road network performance, refinements may be required in specific high-demand scenarios.

Evaluation of a theoretical airport service road network using the established methodology revealed that under representative peak hour conditions (reference case), the network functioned optimally, with no recorded deterioration at any intersection. However, as traffic demand increased by 25% to 50%, small performance declines were observed primarily at four-way priority intersections, emphasising their vulnerability to congestion. Even when traffic volumes were doubled compared to the reference case, the LoS remained acceptable at the 95th percentile, but severe performance drops were recorded at peak time intervals, highlighting the risk of delays in service vehicle deployment.

Assessment of the network using alternative HCM methodologies, based on average travel speed, found that the network operated at LoS “B” for input values up to 125% of the reference case, at LoS “C” up to 175% , and at LoS “D” when traffic doubled. These results align with the LoS classification framework developed in this study, though differences were observed due to factors such as platoon delays and differences in PFFS (Passenger Free-Flow Speed) criteria, which are typically calibrated for urban roadways rather than airport service roads. These findings reinforce the suitability of the methodology for evaluating service road networks provided in this research, while also highlighting potential differences between traditional urban traffic models and airside-specific conditions.

10.2. Implications

10.2.1. Scientific

The scientific knowledge gained from this project provides valuable insights on roadway performance under heterogeneous traffic compositions. Numerous methods for capturing traffic heterogeneity have been documented in the literature and applied to various types of infrastructure used by different vehicle groups. However, the traffic mix present at airport service roads is characterised by an even larger variety of users, each with different performance parameters and maximum vehicle speeds. This leads to a significantly more heterogeneous state of traffic compared to traditional roadway systems. This study has aimed to capture a substantial level of heterogeneity, which exceeds the examples typically found in the literature.

This research has demonstrated that the PCU is an effective method for capturing traffic heterogeneity, even under significantly more heterogeneous conditions. Using MLR, this study has found the PCU values for ten different service vehicles. Analysis have shown that the performance of service vehicles relative to passenger cars is largely dependent on the type of intersection, suggesting that no generalisation can be made on the performance of the service vehicles across entire networks.

While applying the found PCU values, this research has estimated the standardised capacity in terms of PCU per hour for various critical infrastructure components. The standardised capacities have been determined under varying representative traffic compositions and showed consistent results among these conditions, although inconsistencies were measured with more extreme input values. For typical compositions found on service roads however, the PCU values found in this research are valid.

Lastly, the principles of the HCM [58] are effectively applied to service roads, something that has not been studied before in the literature. As a result, the performance of service roads can be assessed qualitatively using a LoS-scale. This research has proven the potential for applying the HCM to non-traditional roadway systems, as the flexibility of this manual was effectively demonstrated.

10.2.2. Practice

This research has provided a method for determining the LoS of service roads, which is accessible and applicable to airport environments. The concept of LoS is well established within the aviation industry, with various other airport systems (security, baggage reclaim, accessibility roads, etc.) being evaluated using the same metric. Airports can evaluate the performance of individual infrastructure components solely on traffic counts, which have to be split between different vehicle types. Traffic counts can be transformed into hourly PCU flow using the PCU values of the service vehicles included in this study. This research has shown that the LoS of five crucial infrastructure components can be determined based on these PCU flows, which has been summarised in a simplified overview (Table 8.3, LoS boundaries expressed in PCU per hour). It is advised to collect traffic count data for small time intervals (approximately five minutes), as this provides more useful information about the evolution of the state of traffic over time.

Furthermore, a framework for determining network performance based on the performance of intersections has been proposed. The network-analysis has provided the aviation industry with an example study where the LoS is determined for a representative pier-configured service road network. The results have shown favourable results under peak hour conditions, as the LoS remained optimal (level “A”) for all simulations. While generalisations for other types of service road networks should be approached with caution, the example study — despite its network complexity and ambitious estimates for vehicle inputs — indicates that the current performance of service roads is very strong, with expected delays of less than 10 seconds for all intersections. Future developments, for example the electrification of service vehicles, may result into additional demand for vehicle movements. The network analysis has proved the importance of re-assessing service road performance if this is true, since the network shows significant drops of performance when the demand is increased by 50% or more.

Looking at individual intersections, this research has indicated that the use of roundabouts should be preferred over four-legged priority intersections at critical points in the network. Roundabouts are less sensitive to the heterogeneity of traffic and facilitate a higher overall traffic flow. Three-way alternative intersections perform considerably worse compared to three-way priority intersections. Considerations regarding possible aircraft taxiing conflicts should however still be made when choosing between the two three-way intersection configurations. Main road segments that are connected to aircraft stands perform well under all network-simulations tested in this research. Additionally, main road segments with multiple aircraft stands (i.e. intersections) have to be analysed as a collective infrastructure component, since the performance of individual intersections is significantly influenced by closely-positioned aircraft stand intersections upstream and downstream.

Practical steps for airport planners

Following the findings of this research, it is advised to apply this study to a real-life airport case study where performance-related issues with service road traffic are reported. It is probable that issues do not occur across entire service road networks, and therefore for many airports it is recommended to first look at specific infrastructure components that are subjected to high traffic volumes (i.e. bottlenecks). This saves costs for airports, which stimulates them to perform effective performance evaluation. This can be achieved by simply counting the number of service vehicles of each type during several small time intervals, recorded during peak hour conditions. Multiplying the vehicle counts with their corresponding PCU value found in this research results into a PCU flow (expressed in PCU per hour), which is able to estimate the LoS based on the PCU boundaries presented in this study (see Table 8.3 for LoS boundaries expressed in PCU per hour).

When multiple components are subjected to congestion, it is sensible to upscale the analysis to a (section of) a service road network. This means that the LoS of the network has to be estimated following the method explained in Chapter 9 (Network-level traffic modelling and analysis). This requires more effort and resources, but this would be justified in case of large delays as this can have a substantial impact to the timely turnaround of aircraft. Additionally - although not extensively covered in this research - network-level analysis allows for exploring traffic management strategies, such as the use of alternative routes, implementing traffic lights or improving infrastructure to enhance efficiency.

An even better suggestion is to apply the performance estimation framework to greenfield projects, which prevents or decreases the likelihood of congestions at future airports. This would however require detailed simulation models of the airside environment. Airport planners utilise software such as CAST airport simulation [4], enabling comprehensive analysis based on realistic operational scenarios. CAST has a dedicated module for vehicle ground handling, which is able to extract traffic counts at specified locations as well. This can be used to accurately estimate the LoS for service roads, drawing on specialised traffic engineering insights from this study. Combining airport-specific software with the findings from this research would create a strong synergy, enhancing the overall analysis and operational efficiency of new airports.

10.3. Limitations

This section outlines the limitations of the study, highlighting the constraints and potential areas for improvement that should be considered when interpreting the results. First, a limitation of this research is neglecting to account for interaction effects between different vehicle types in the MLR model used to determine PCU values. By not including interaction terms, the model may not accurately capture how the presence of one vehicle type could influence the delay effects of another, particularly in combinations that might significantly alter traffic dynamics. Consequently, the derived PCU values might not fully reflect the complex interdependencies of vehicle interactions. A simplified straight road segment VISSIM model has been created to account for these delay effects.

Additionally, despite having made substantial efforts into analysing various types of vehicles, the characteristics (size, speed, acceleration, etc.) of the vehicles can vary as well. Within this research, an assumption was made regarding the physical and behavioural parameters of service vehicles, while in reality these parameters are dependent on other (external) factors too. This ultimately also affects the determination of PCU values and subsequent performance in practice. However in the literature, various basic methods exist for estimating PCU values [42], which can then be calibrated for the application to service roads based on this research.

Simplifications have been made for the modelling and analysis of main road segments. These are analysed using a VISSIM model with three aircraft stands, while the findings have been generalised for further interpretation in this research. Main road segments may vary in length, number of aircraft stands, and distance between aircraft stands. The length of the segment and number of stands have been accounted for by linearly extrapolating the findings from the main road segment model with three aircraft stands, while the distance between aircraft stands has not been taken into consideration. This limits the validity of the results for main road segments.

Furthermore, capacity and LoS analyses conducted during the component-level modelling phase of this research have demonstrated that, although capacity and LoS boundaries remain largely consistent across a wide range of traffic compositions typically found at airports, the LoS boundaries are not universally applicable to all traffic mixes. A stress-test was performed using a “passenger car only” traffic flow, and the results showed significant inconsistencies using the PCU values found in this research. However, this traffic composition is not typically found on service roads, therefore limiting the impact of this limitation. Additionally, extra validation of the LoS boundaries was performed on the network-level model with larger variations of vehicle mixes, achieving an accuracy of 97.8% for all intersection LoS measurements. This proves that the PCU values are robust under a large variety of traffic compositions.

Lastly, while arguments have been given for altering the criteria that determined the LoS of component-level intersections, a more analytical approach is needed to further align with airside operational requirements. The LoS criteria expressed in seconds of intersection delay are deferred from the HCM, which are based on perceived user satisfaction for urban roadways [58]. However, the perceived user satisfaction might differ from traditional road users. It is expected that the acceptance for delay is lower in environments such as airports, given the time-criticality of its operations. Since this expectation was not proven in this research, this has not been further taken into consideration.

10.4. Recommendations for future research

This section provides relevant recommendations for future research that can build on the methods applied in this research. First, this is a simulation-based study that has made considerable efforts to replicate service road environments, but the results of the study have not been validated using real-life data. This data is likely lacking because airports have not yet prioritised analysing the traffic performance of these systems, as issues and concerns are only beginning to emerge at larger airports [49]. Comparing the performance resulting from the methodology provided in this research with observations from critical bottlenecks at airport service roads would be appropriate validation of this research. Further calibrations for PCU values and the subsequent performance measures can be made using this data.

Additionally, this research has not included all infrastructure components in this research. Even though the five included components comprise the most critical parts of service road networks, variations of these configurations exist. This means that it requires traffic engineering knowledge to estimate how these variations impact the performance of such infrastructure components. Examples could be the implementation of stop signs, three-way or five-way roundabouts, or uncontrolled intersections. Further research may be required to accurately estimate the performance of these variations.

Further improvements to the estimation of the LoS of service roads can be made by considering different turning rates at intersections, which has not been included in this research. This results into varying degrees of conflicting flows, which can improve or limit the performance and capacity of intersections. In this research, reasonable and typical turning rates were used for all analyses.

10.5. Conclusions

This research has concluded that the performance of individual airside service road infrastructure components can effectively be determined through a combination of PCU analysis, capacity estimation, and LoS assessment. The research demonstrated that traffic heterogeneity significantly impacts infrastructure performance, which highlights the importance of conversing vehicle flows into standardised PCU flows. By utilising a microscopic traffic simulation approach, it was concluded that PCU values differed considerably across different intersection types, indicating that the performance of service vehicles relative to passenger cars is dependent on the type of intersection. Performance analysis showed that, despite having significantly higher PCU values, the absolute throughput of four-way priority intersections remained competitive to other intersections. However, the performance of service vehicles relative to passenger cars was more negatively impacted , hence the high PCU values. Conversely, roundabouts exhibited more stable performance, and accommodated service traffic more efficiently. The implementation of three-way alternative intersections at critical network locations can lead to operational challenges due to their limited overall capacity. The establishment of LoS boundaries in PCU per hour allowed for a concise evaluation of individual infrastructure component performance, making the method accessible for various airport service roads.

The methodology developed for individual infrastructure components was upscaled to a network-level model, which demonstrated its applicability for the evaluation of airside service road performance on a larger scale. The study found that LoS boundaries established at the component level remained largely applicable to the entire network, with a validation accuracy of 99.3% across all intersections. The LoS determination method, based on aggregating individual intersection performance, provided a structured approach to evaluating bottlenecks and identifying critical infrastructure elements within the network. The network simulation revealed that four-way priority intersections consistently performed worse under increased traffic demand, while roundabouts showed greater resilience. Additionally, the analysis confirmed that even under high traffic volumes (up to 200% of the reference case), the network maintained an acceptable LoS at the 95th percentile, although severe local congestions occurred at specific intersections and time intervals. These results highlight the effectiveness of the standardised LoS methodology in assessing network-wide service road performance.

This research provides a standardised and widely applicable method for estimating the performance of airside service roads across different airport environments. The methodology integrates PCU-based traffic modelling, capacity estimation, and LoS determination, which therefore offers a comprehensive framework for assessing service road performance at both component and network levels. The findings show that PCU values must be calculated per infrastructure component type, as they vary significantly between different intersections. Additionally, while LoS thresholds remain relatively stable, variations in traffic composition can cause minor discrepancies, slightly impacting the accuracy of the performance estimation. By validating the methodology on a representative network, this research confirms its applicability beyond a single airport, making it a valuable tool for airport planners and engineers seeking to optimise airside traffic management.

In conclusion, the standardised performance estimation method developed in this study bridges the gap between traditional traffic engineering approaches and the unique operational challenges of airside service roads. It provides a data-driven foundation for future infrastructure planning, which ensure that airports can evaluate and optimise service road networks in response to growing operational demands.

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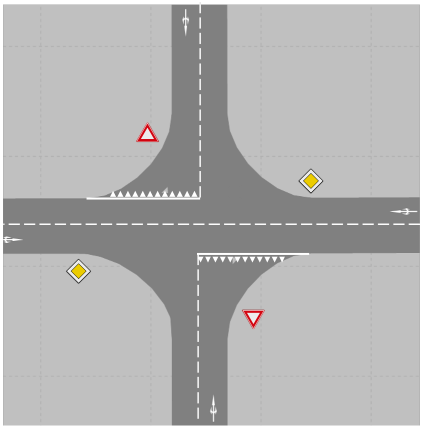
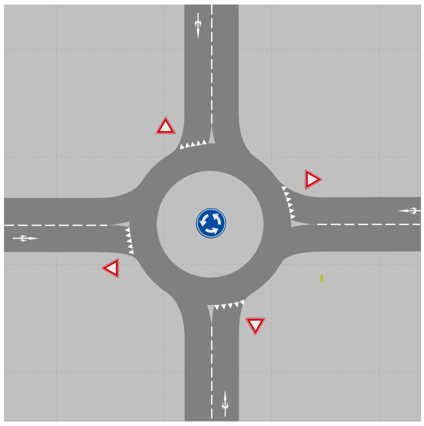
A

Appendix: VISSIM-models

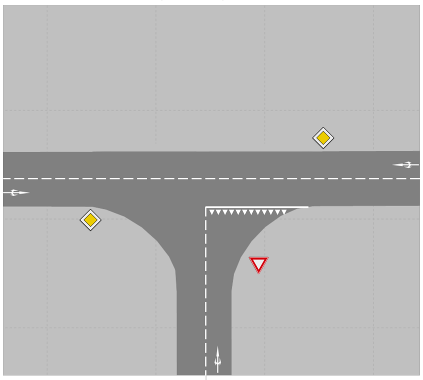
A.1. Component-level models



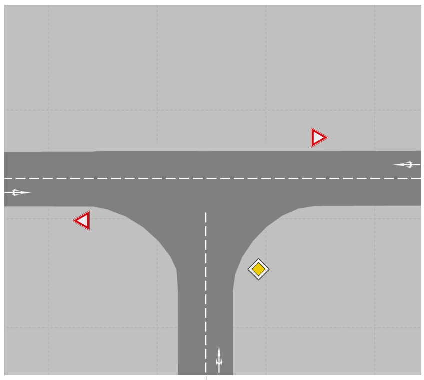
(a) 4-way priority intersection



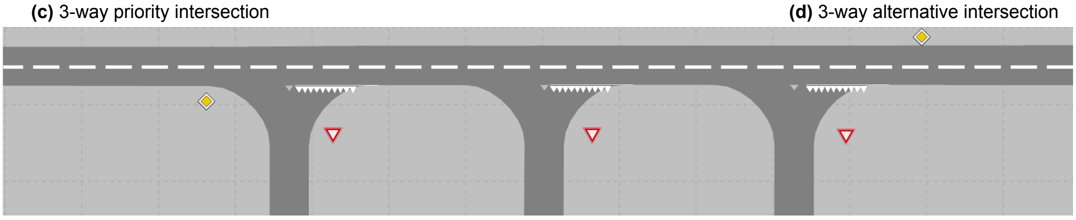
(b) 4-way roundabout intersection



(c) 3-way priority intersection



(d) 3-way alternative intersection



(e) Main road segment with 3 aircraft stands

Figure A.1: Model implementation in VISSIM

A.2. Network-level models

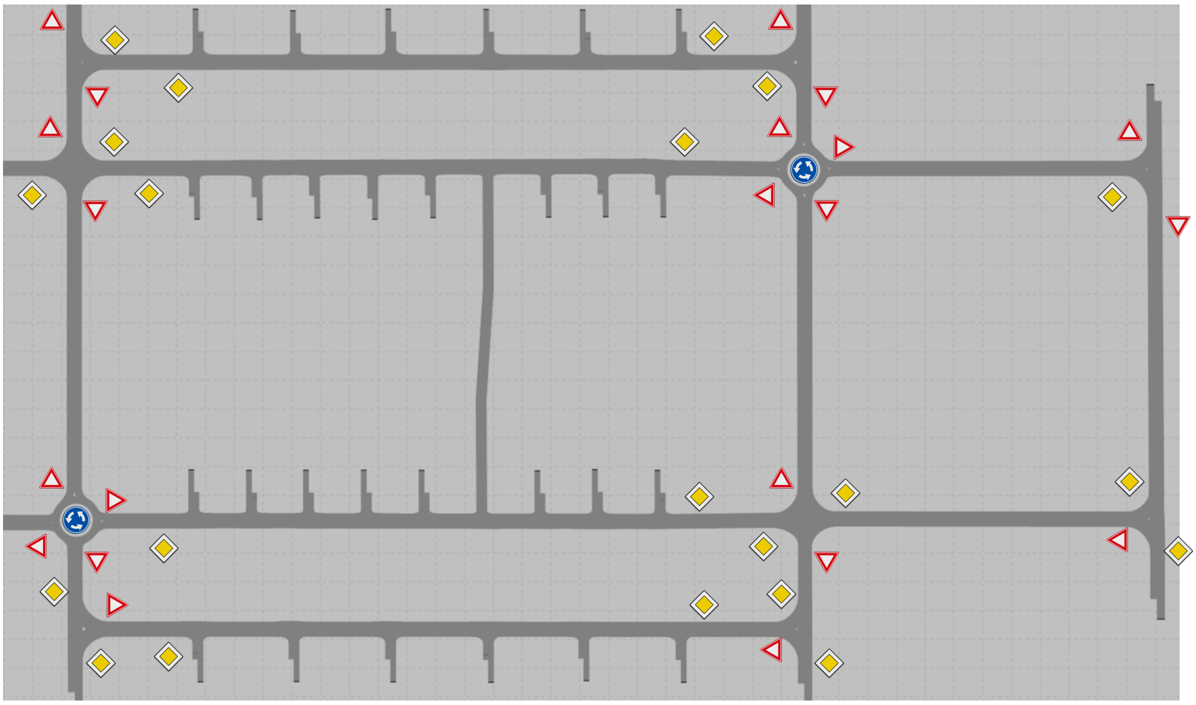
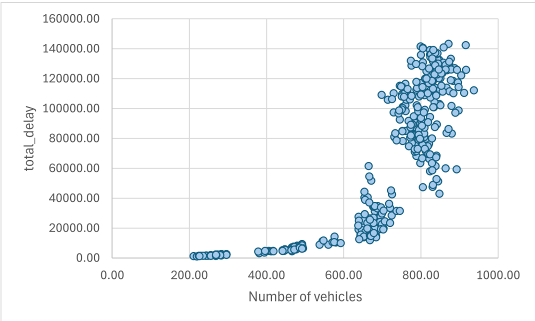
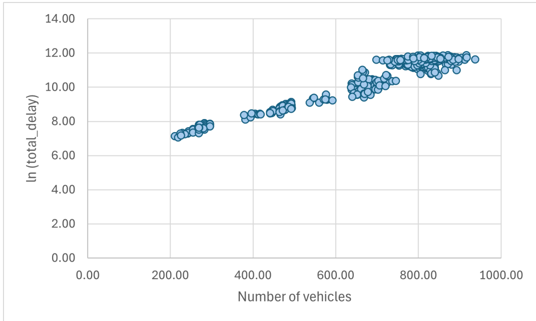


Figure A.2: Priority rules of all intersections (nodes) in the network model

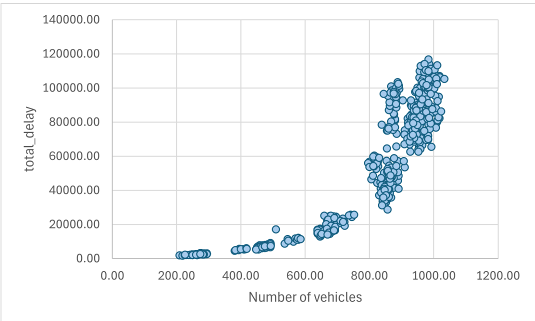
B
Appendix: Passenger Car Unit results



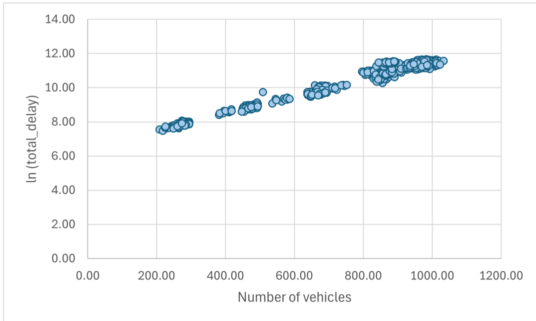
(a) 4-way priority intersection



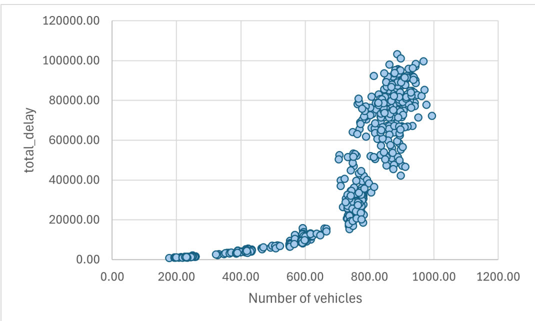
(b) 4-way priority intersection, natural logarithm



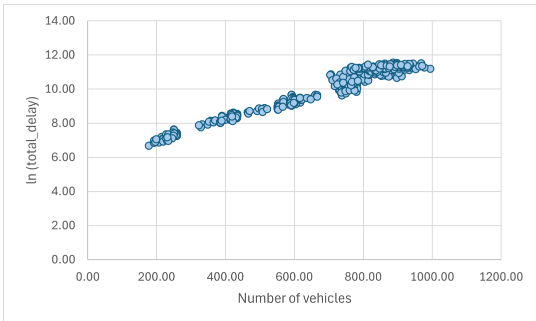
(c) 4-way roundabout intersection



(d) 4-way roundabout intersection, natural logarithm

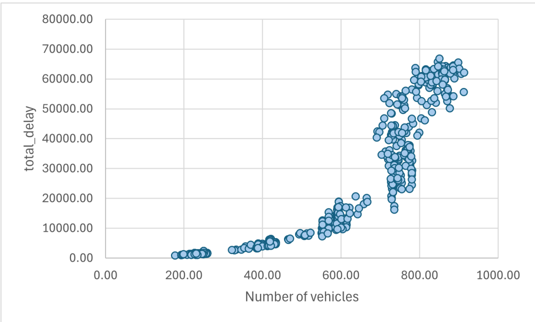


(e) 3-way priority intersection

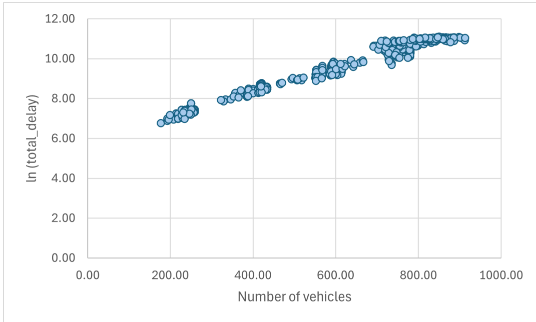


(f) 3-way priority intersection, natural logarithm

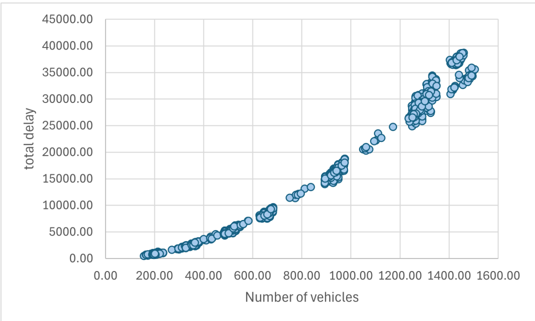
Figure B.1: Scatter plots of infrastructure components, normal and natural logarithm, part 1



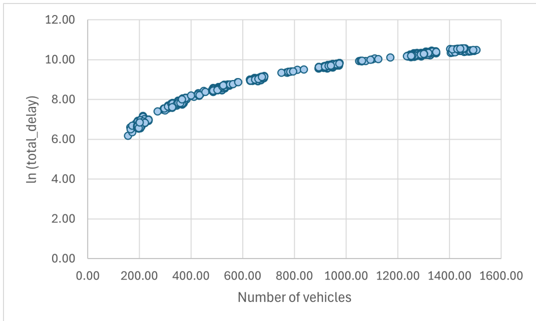
(a) 3-way alternative intersection



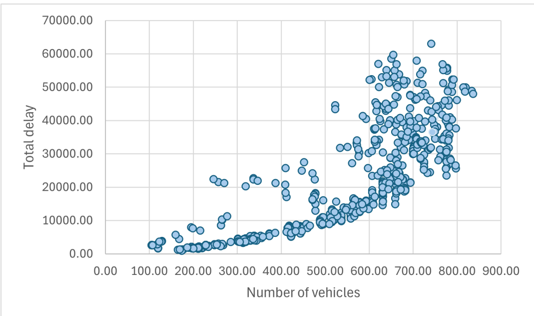
(b) 3-way alternative intersection, natural logarithm



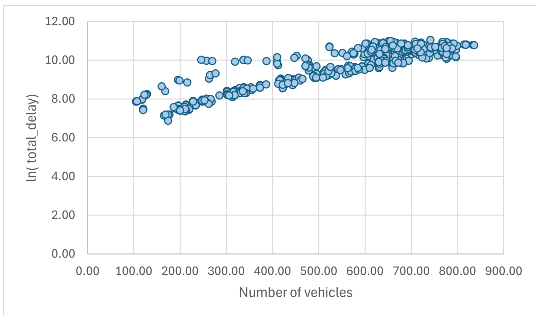
(c) Straight segment



(d) Straight segment, natural logarithm



(e) Main Road Segment



(f) Main road segment, natural logarithm

Figure B.2: Scatter plots of infrastructure components, normal and natural logarithm, part 2

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	5.526971	.031		179.730	<.001
	num_car	.002957	.000	.069	8.901	<.001
	num_bus	.006947	.000	.122	17.481	<.001
	num_cat	.006595	.000	.179	19.932	<.001
	num_fuel	.007764	.000	.169	23.800	<.001
	num_clean	.004507	.000	.092	12.655	<.001
	num_toilwater	.007026	.000	.170	20.311	<.001
	num_baggage	.010440	.000	.280	34.620	<.001
	num_cargo	.010852	.000	.224	32.864	<.001
	num_pushback	.006314	.000	.148	21.172	<.001
	num_belt	.007230	.000	.162	21.204	<.001
	num_high	.008692	.000	.175	26.160	<.001

(a) 4-way priority intersection

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	6.434270	.012		528.923	<.001
	num_car	.003260	.000	.102	26.554	<.001
	num_bus	.005426	.000	.132	38.739	<.001
	num_cat	.005223	.000	.201	45.282	<.001
	num_fuel	.005451	.000	.168	48.591	<.001
	num_clean	.003405	.000	.096	26.972	<.001
	num_toilwater	.004834	.000	.165	39.977	<.001
	num_baggage	.007451	.000	.273	69.694	<.001
	num_cargo	.007586	.000	.220	66.094	<.001
	num_pushback	.004275	.000	.132	38.197	<.001
	num_belt	.004201	.000	.142	38.821	<.001
	num_high	.004980	.000	.141	42.972	<.001

(b) 4-way roundabout

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	5.742486	.019		308.729	<.001
	num_car	.003368	.000	.085	15.862	<.001
	num_bus	.005774	.000	.116	23.926	<.001
	num_cat	.006079	.000	.187	29.826	<.001
	num_fuel	.006233	.000	.148	30.090	<.001
	num_clean	.004441	.000	.099	19.631	<.001
	num_toilwater	.006078	.000	.170	28.406	<.001
	num_baggage	.008801	.000	.263	46.470	<.001
	num_cargo	.009104	.000	.206	43.842	<.001
	num_pushback	.005434	.000	.132	26.908	<.001
	num_belt	.005349	.000	.142	27.337	<.001
	num_high	.007624	.000	.167	36.466	<.001

(c) 3-way priority intersection

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	5.880693	.017		350.871	<.001
	num_car	.003395	.000	.084	15.298	<.001
	num_bus	.005905	.000	.114	23.417	<.001
	num_cat	.006527	.000	.203	31.312	<.001
	num_fuel	.005951	.000	.147	29.444	<.001
	num_clean	.004514	.000	.099	19.160	<.001
	num_toilwater	.005775	.000	.159	25.969	<.001
	num_baggage	.008530	.000	.261	45.771	<.001
	num_cargo	.008414	.000	.198	41.588	<.001
	num_pushback	.005534	.000	.137	27.693	<.001
	num_belt	.005141	.000	.140	26.644	<.001
	num_high	.007056	.000	.159	34.226	<.001

(d) 3-way alternative intersection

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	6.71526658	.034		196.862	<.001
	num_car	.00330777	.000	.096	6.943	<.001
	num_bus	.00480493	.001	.115	9.351	<.001
	num_cat	.00446465	.000	.160	10.084	<.001
	num_fuel	.00551896	.000	.148	11.678	<.001
	num_clean	.00347802	.001	.086	6.864	<.001
	num_toilwater	.00398726	.000	.132	8.874	<.001
	num_baggage	.00728247	.000	.244	16.979	<.001
	num_cargo	.00729762	.000	.200	16.421	<.001
	num_pushback	.00643755	.000	.177	14.104	<.001
	num_belt	.00547357	.000	.174	12.901	<.001
	num_high	.00626606	.000	.162	13.670	<.001

a. Dependent Variable: ln_delay

(e) Main road segment

Coefficients[a]

Model		Unstandardized Coefficients B	Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-8072.355	160.135		-50.410	<.001
	num_car	27.247	2.233	.109	12.204	<.001
	num_bus	30.482	2.360	.094	12.914	<.001
	num_cat	34.882	2.017	.203	17.290	<.001
	num_fuel	34.520	1.920	.140	17.980	<.001
	num_clean	28.106	2.326	.096	12.081	<.001
	num_toilwater	35.607	2.101	.183	16.943	<.001
	num_baggage	25.309	1.522	.151	16.634	<.001
	num_cargo	24.086	1.619	.102	14.878	<.001
	num_pushback	22.522	1.600	.103	14.072	<.001
	num_belt	23.103	1.560	.119	14.806	<.001
	num_high	21.551	1.644	.086	13.113	<.001

a. Dependent Variable: total_delay

(f) Straight segment, no natural logarithm

Figure B.3: Results Multiple Linear Regression SPSS

C

Appendix: Network analysis results

C.1. Network Level of Service results

Table C.1 reports the counts of every LoS across all scenarios and intersections on the left. In other words, it is counted how many times an intersection was assigned a certain LoS. On the right hand side, it is counted how many vehicles have experienced the LoS on that particular intersection type. The main findings from the statistics presented underneath have been reported in subsection 9.2.2.

Counts							Vehicles					
Reference												
Intersection	A	B	C	D	E	F	A	B	C	D	E	F
4prio	240	0	0	0	0	0	4308	0	0	0	0	0
4round	240	0	0	0	0	0	4296	0	0	0	0	0
3prio	600	0	0	0	0	0	4704	0	0	0	0	0
3alt	360	0	0	0	0	0	4640	0	0	0	0	0
main road	480	0	0	0	0	0	6327	0	0	0	0	0
Reference +25%												
Intersection	A	B	C	D	E	F	A	B	C	D	E	F
4prio	238	0	2	0	0	0	5290	0	89	0	0	0
4round	240	0	0	0	0	0	5371	0	0	0	0	0
3prio	600	0	0	0	0	0	5836	0	0	0	0	0
3alt	360	0	0	0	0	0	5777	0	0	0	0	0
main road	480	0	0	0	0	0	7910	0	0	0	0	0
Reference +50%												
Intersection	A	B	C	D	E	F	A	B	C	D	E	F
4prio	225	11	4	0	0	0	5808	457	189	0	0	0
4round	239	1	0	0	0	0	6410	44	0	0	0	0
3prio	600	0	0	0	0	0	7153	0	0	0	0	0
3alt	360	0	0	0	0	0	6960	0	0	0	0	0
main road	480	0	0	0	0	0	9545	0	0	0	0	0
Reference +75%												
Intersection	A	B	C	D	E	F	A	B	C	D	E	F
4prio	201	22	10	2	1	1	5569	952	465	106	51	61
4round	231	6	0	0	0	0	6979	280	0	0	0	0
3prio	596	1	0	0	0	0	8093	46	0	0	0	0
3alt	357	0	0	0	0	0	7894	0	0	0	0	0
main road	476	0	0	0	0	0	10755	0	0	0	0	0
Reference +100%												
Intersection	A	B	C	D	E	F	A	B	C	D	E	F
4prio	171	14	28	6	8	1	4586	626	1339	303	432	62

4round	206	17	3	0	0	0	6429	872	155	0	0	0
3prio	580	5	0	0	0	0	8374	255	0	0	0	0
3alt	343	7	3	0	0	0	7816	326	162	0	0	0
main road	463	0	0	0	0	0	11206	0	0	0	0	0

Table C.1: Statistics Level of Service determination per intersection (left) and per vehicle (right), all intersections, all scenarios

C.2. Level of Service boundary validation

Table C.2 underneath presents an overview of all 31 mismatches that are reported in Section 9.3.2. The columns indicate (from left to right): the type of intersection, vehicles per hour (all types), PCU per hour based on the MLR model, estimated Level of Service, lower bound (LB) in PCU/hour of the associated estimated Level of Service, upper bound (UB) in PCU/hour of the associated estimated Level of Service, the observed difference of the mismatch.

The average of the difference is 23.3 PCU/hour. The maximum difference is 97.0 PCU/hour. The standard deviation of the difference is 23.1 PCU/hour. All intersection types are represented in the mismatches. The four-way intersections do occur more often in this list. This can be explained because of the positioning of this intersection in the network, as the Westside intersections are important bottlenecks within the system. This results into higher average traffic volumes (in terms of vehicles/hour and PCU/hour), which makes the change of a mismatch higher. Mismatches are namely exclusively observed for volume levels higher than 985 PCU/hour.

Intersection	Vehicles/hour	PCU/hour	Est. LoS	PCU/hour LB	PCU/hour UB	Difference
3alt	552	1051	B	1054	1154	3
3alt	576	1072	A	0	1054	18
3alt	600	1092	A	0	1054	38
3alt	624	1170	B	1054	1154	16
3alt	528	1020	B	1054	1154	34
3prio	576	1132	A	0	1114	18
3prio	600	1135	A	0	1114	21
4prio	540	1401	C	1414	1561	13
4prio	516	1360	C	1414	1561	54
4prio	552	1345	A	0	1305	40
4prio	552	1309	A	0	1305	4
4prio	504	1301	B	1305	1414	4
4prio	516	1316	A	0	1305	11
4prio	564	1372	A	0	1305	67
4prio	660	1578	C	1414	1561	17
4prio	612	1467	B	1305	1414	53
4prio	576	1548	D	1561	1662	13
4prio	636	1652	E	1662	1776	10
4prio	576	1402	A	0	1305	97
4prio	648	1647	E	1662	1776	15
4prio	564	1549	D	1561	1662	12
4round	576	1017	C	1087	1216	70
4round	624	992	A	0	991	1
4round	600	992	A	0	991	1
4round	600	999	A	0	991	8
4round	576	985	B	991	1087	6
4round	600	987	B	991	1087	4
4round	624	1002	A	0	991	11
4round	624	1005	A	0	991	14
4round	660	1017	A	0	991	26
4round	624	1064	C	1087	1216	23

Table C.2: Overview mismatches of boundary analysis

D Scientific paper

In this appendix, the scientific paper written for this thesis project is presented. The scope of the article differs slightly from the thesis project, with greater emphasis placed on the component-level models and the findings of the PCU calculation (Chapter 6), capacity estimation (Chapter 7), and LoS determination (Chapter 8). The network-level section of this thesis project is largely excluded from the paper, as it primarily extends the prior analyses.

Towards a standardised method for airside service road performance assessment using PCU-based traffic modelling

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March 27, 2025

Abstract

Airside service roads are essential for the movement of ground support vehicles that enable efficient aircraft turnaround and overall airport operations. Despite their importance, no standardised method exists for evaluating their capacity and performance, limiting the ability of airports to optimise this operational infrastructure. However, the heterogeneity of service road traffic — characterised by vehicles with varying speeds, sizes, and manoeuvrability — complicates capacity estimation and Level of Service (LoS) assessment. This research shows that a combination of microscopic traffic simulation and Multiple Linear Regression (MLR) provides a robust framework for estimating Passenger Car Unit (PCU) values and evaluating service road performance. Using five common airside road configurations, the method estimates PCU values for eleven service vehicle types and establishes LoS boundaries expressed in PCU per hour. The results reveal that PCU values vary significantly across intersection types, with four-way priority intersections exhibiting the highest sensitivity to traffic heterogeneity. Roundabouts are found to facilitate smoother traffic flow. Two three-way intersection types provide similar PCU values, but traditional priority rules facilitate substantially better performance. These findings provide a standardised method for assessing airside service roads, enabling airports to improve infrastructure planning and mitigate congestion amid rising aviation demands.

Introduction

The projected 5% annual increase in air travel passenger demand over the coming decades [1] is expected to significantly intensify the pressure on airport airside facilities and operations. Without improvements in airport efficiency, this growth will be constrained, potentially stalling the momentum of the aviation industry [2]. Ground operations, including baggage and passenger handling, fuelling, servicing, and aircraft maintenance, must adapt to this rapid growth by optimising available resources. These services are crucial for minimising aircraft turnaround time, which is vital for maintaining the competitive edge of airports and airlines [3].

A critical yet often overlooked component of airside infrastructure is the service roadway system. These roads are essential for the movement of service vehicles that support efficient and timely aircraft turnaround. As airports expand, service roads face increased congestion, particularly during peak hours. Understanding the performance of these roads is crucial for ensuring timely aircraft departures. However, there is currently no clear method to determine the capacity and performance of service roads. While comprehensive methods exist for traditional roadway infrastructure [4, 5], similar approaches for airside service roads are lacking.

The complexity of airside service road systems, despite their simple layouts, arises from the diverse range of vehicles using them. These vehicles exhibit different behaviours due to variations in speed, acceleration, deceleration, size, and manoeuvrability, leading to significant traffic heterogeneity. This heterogeneity complicates the determination of operational performance, making it essential to accurately represent the varying traffic mix. Although extensive research has been conducted on methods to capture traffic heterogeneity [6, 7, 8, 9], none has been specifically applied to airside service roads.

This research aims to fill this gap by developing a standardised method for assessing the capacity and performance of service road infrastructure components, based on PCU calculations that capture the traffic heterogeneity. The methodology integrates PCU-based traffic modelling, capacity estimation, and Level of Service (LoS) determination, and offers a comprehensive framework for evaluating service road performance. By using microscopic simulation models, this study aims to provide a higher standard of traffic engineering analysis compared to current methods used within the aviation industry. Additionally, the research seeks to develop an evaluation methodology that is widely applicable to various airports, rather than being tailored to a specific location. This comprehensive framework will enable airports to evaluate and optimise their service road networks in response to growing operational demands.

Literature

Research has found that speed, size, acceleration capability, and manoeuvrability are important indicators for PCU estimation [10]. Due to the variation in these factors among service road users included in this study, it is anticipated that different vehicle types will significantly impact infrastructure performance and limit the capacity in terms of vehicles per hour. Research on service road systems at Amsterdam Schiphol Airport [11] has shown that there is indeed a large variety of users, each with different physical and behavioural characteristics. Although the maximum speed on airport service roads is generally around 30 km/h [12], the Schiphol Airport case study revealed that many vehicles commonly deployed at airports are limited to speeds of approximately 15 km/h. Combined with the large footprint of these vehicles, this traffic heterogeneity significantly impacts traffic performance.

In the literature, PCU, also referred to as Passenger Car Equivalent, is often used to compare the impact of different vehicle types on traffic performance indicators such as delays, travel time, or travel speed [5]. Comparative analysis of methods for estimating PCU values on unsignalised intersections [13] suggests three alternatives for PCU estimation: based on occupancy time, capacity or queue clearance rate. Each method compared in this research provided logical and representative PCU values.

However, a literature review of methodologies for PCU analysis [14] has revealed inconsistencies in the resulting PCU values across different methods, highlighting the importance of choosing the most appropriate method. Research on highly heterogeneous conditions [6] has concluded that Multiple Linear Regression (MLR) is especially appropriate when traffic is subjected to large variations in physical and behavioural characteristics, which indicates its potential for airport service road systems. An application of this method on urban intersections [8] has concluded that MLR is effective, efficient, and appropriate for estimating PCU values under heterogeneous traffic conditions. This research was conducted in the Indonesian city of Banda Aceh, where roads are subjected to a large variety of vehicle users: motorcycles, passenger cars, motorized rickshaws, and different-sized trucks and buses. Despite its value for determining PCUs under these conditions, the degree of heterogeneity on airport service roads is even more intense.

Comparative studies of PCU estimation methods by Mondal et al. [7] and Raj et al. [15] have also acknowledged that MLR is one of the most useful techniques for determining PCU values at intersections. Various implementations of MLR applied to roadway systems to obtain PCU values exist in the literature. Research analysed [7, 15, 8] uses the number of vehicles of each vehicle type i as independent variables for the MLR model. An advantage of this method is that it allows direct comparison of the regression coefficients for each vehicle type.

The choice of the dependent variable varies and mostly depends on the focus of the study. Highway applications are often modelled using Free Flow Speed, while in urban environments and intersections, it is more useful to calculate the experienced delay, as indicated by the Highway Capacity Manual [5]. PCU estimations based on delay by Raj et al. [15] allow for computing the delay experienced by one driver as the difference between the delay of a vehicle i and the "base" delay, which is considered the delay of the reference vehicle (passenger car).

Methodology

Microscopic traffic simulation

Among microscopic, macroscopic and mesoscopic simulation, microscopic aggregation level was chosen to accurately represent the traffic heterogeneity present on airport service roads. This allows the model to retrieve data specific to distinct service vehicle types by representing their unique characteristics such as speed, acceleration and deceleration, and the interaction between vehicles (car-following, priority giving), accurately.

Microscopic traffic simulation software PTV VISSIM is used for this research to capture the aforementioned aspects. VISSIM is appropriate for this research due to its extensive use in traffic engineering and its strong support and documentation. Additionally, a prior study on Amsterdam Schiphol Airport [11] has demonstrated the potential of using this software for service roads specifically, highlighting its flexibility to non-traditional roadway systems.

Five infrastructure components are modelled in VISSIM, as this research aims to elucidate whether traffic heterogeneity can be consistently captured across entire service road networks, or if a distinction should be made between different infrastructure components. The service road components that are frequently found at airports and modelled in this research are: four-way priority intersection, four-way roundabout, three-way priority intersection, three-way alternative intersection, and a main road segment. A demonstration of the models and their priority rules are presented in Figures 1 and 2. Three-way alternative intersection follows non-traditional priority rules, giving priority to one direction only. This direction intersects with aircraft taxiways, and delays caused by service vehicles are unacceptable to airports. Main road segments represent a critical part of service road networks, as these are the roads facilitating movements towards and from the aircraft stands. All other models follow traditional priority rules.

This research has included the most important service vehicles that are required to service aircraft, and represent the vast majority of vehicles present on airport service roads. Each aircraft type requires a different number of service vehicles, thereby impacting the traffic composition of service roads. As highlighted by De Jong [11], a simplification about the number of vehicles needed can be made between narrow-body and wide-body aircraft. Furthermore, the deployment of buses is primarily dependent on the type of stands being used by the airport, as remote stands are situated further away from the terminal building and require people movers to connect the terminal with the aircraft. These factors, along with data from narrow-body and wide-body aircraft [16, 17, 18, 19], resulted in the share of the base traffic composition presented in Table 1. This composition is used for the VISSIM simulations. Furthermore, Table 1 reports the most important vehicle parameters that are used for each vehicle type. Speed profiles are derived from the Amsterdam Schiphol Airport case study [11], with further adjustments on them as well as acceleration and deceleration values sourced from research of urban intersection speed profiles [20, 21, 22]. These profiles are based on data of light and heavy vehicles, with further corrections made to baggage and cargo trains to account for their poor manoeuvrability.

Multiple Linear Regression

PCU values are estimated using Multiple Linear Regression (MLR). The total delay of each simulation run is used as the dependent variable for this analysis. The independent variables are the number of vehicles for each vehicle type *i*. Since this research is interested in capturing the traffic heterogeneity for different parts of the service road network, the PCU values are also calculated for each infrastructure component *j*. This validates whether the PCU values are consistent across the entire network, or if there are substantial differences between infrastructure components. The MLR model is created using statistical software package SPSS.

Prior to this analysis, it is hypothesised that the relationship between the number of vehicles (independent variables) and total delay (dependent variable) was exponential rather than linear. Initial simulation runs have confirmed that the relationship is indeed exponential, supporting the hypothesis. Therefore, the natural logarithm of total delay has been taken, leading to a linear relationship between the dependent and independent variable. This results in the following linear regression model for each infrastructure component:

$$\ln(\mathrm{D}_j) = \beta_{0j} + \sum_{i \in I} \beta_{ij} \cdot \mathrm{N}_i \qquad \forall j \in J \tag{1}$$

where:

D_j : Total delay of infrastructure component j

β_{0j} : Regression constant (intercept) of infrastructure component j

β_{ij} : Regression coefficient of vehicle type i and infrastructure type j

N_i : Number of vehicles of type i

Subsequently, the PCU values for each vehicle type i on infrastructure-component j is calculated by dividing the regression coefficient β_{ij} by the regression coefficient of the passenger car $\beta_{\mathrm{car}j}$, which is the reference for this analysis. This is explained in the following mathematical formulation:

$$\mathrm{PCU}_{ij} = \frac{\beta_{ij}}{\beta_{\mathrm{car}j}} \qquad \forall i \in I, \forall j \in J \tag{2}$$

where:

PCU_{ij} : Passenger Car Unit of vehicle type i at infrastructure component j

$\beta_{\mathrm{car}j}$: Regression coefficient of passenger car at infrastructure component j

Service road performance

Using PCU values found in this research, an estimation of the performance of service roads is made using the Highway Capacity Manual (HCM) [5]. Figure 3 provides an overview of the methodology used for the determination of performance of service road infrastructure components. It highlights its integration with the PCU values and MLR model explained in previous section.

The methodology of the performance estimation is divided in capacity analysis and Level of Service (LoS) analysis, while simulation and PCU analysis are explained in previous sections. Capacity analysis defines the upper limit of vehicle movements each

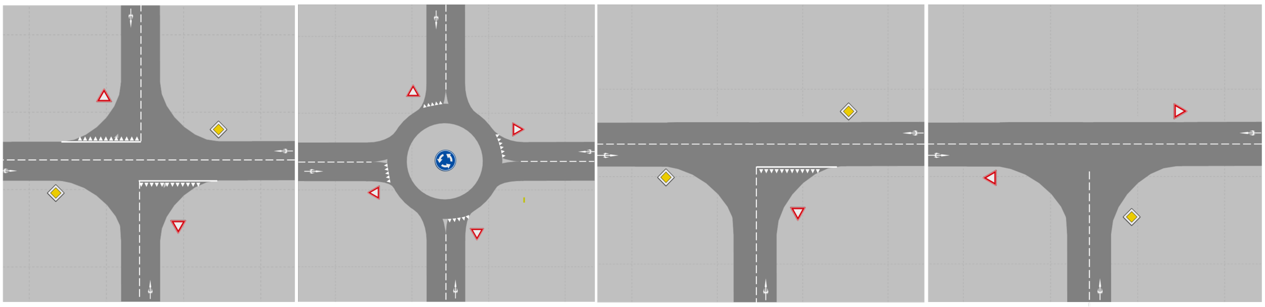

Figure 1: VISSIM: Four-way priority, four-way roundabout, three-way priority and three-way alternative intersection

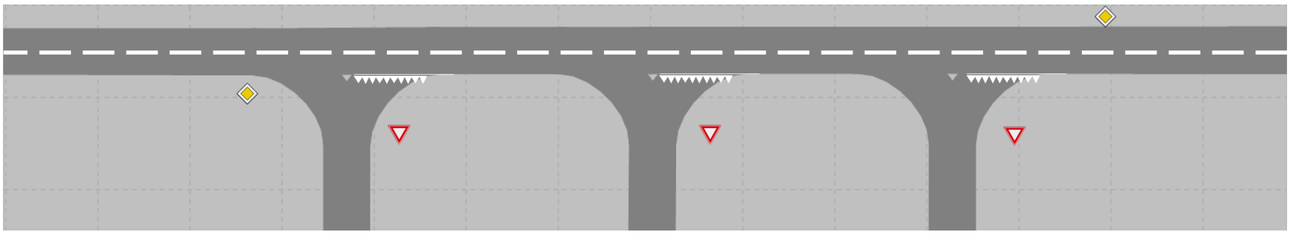

Figure 2: VISSIM: Main road segment with three aircraft stands

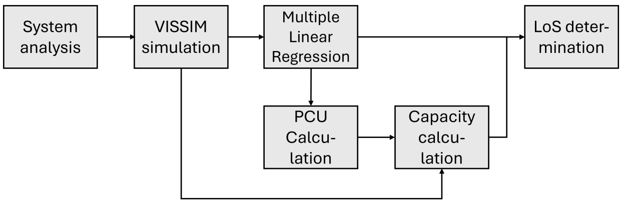

Figure 3: Methodology overview

infrastructure component can realistically facilitate. The capacity of each infrastructure component has been determined by over-saturating the model, causing an unstable traffic system where not one vehicle could be added [23]. Capacity is expressed in PCU per hour, using PCU values for specific infrastructure components calculated from the MLR models. Capacity is an essential element in the estimation of the service road performance.

The performance of individual infrastructure components is qualitatively expressed using a LoS-scale. The criteria determining the LoS are described in the HCM [5]. In Table 2, the criteria for each distinct service level is expressed in seconds of intersection delay per vehicle.

The MLR model presented in the methodology section predicts the total delay rather than the pure intersection delay, which is needed to obtain the LoS indication. The total delay can effectively be split into two elements: intersection delay and platoon delay. Intersection delay is the delay that is caused by the control of the intersection, and entails vehicles waiting to be served by the intersection [5].

Platoon delay on the other hand, is caused by a series of vehicles travelling closely to each other, where the speed of the following vehicles are limited by the speed of the leading vehicle. The leading vehicle is in free flow and therefore does not experience any delay, while the following vehicles are impeded by the leader. This type of delay is not attributable to the intersection itself, but is rather a result of the heterogeneity of traffic.

To correct for this phenomenon, delay decomposition is performed. A simplified VISSIM simulation is set up to correct for platoon delay. A straight segment of the same size as the infrastructure components is modelled, without the actual intersections. The total delay, which is the platoon delay in this case, and vehicle numbers from this simulation are used in a MLR model, in an identical manner as previously explained in the methodology. The intersection delay D_j^{int} is calculated by subtracting the platoon delay D_j^{plat} from the total delay D_j. Platoon delay should be at least zero under all circumstances.

$$D_j^{\text{int}} = D_j - \max(0, D_j^{\text{plat}}) \qquad \forall j \in J \tag{3}$$

The service road performance analysis results in an overview presenting the boundaries expressed in terms of PCU per hour for each service level and infrastructure component. This can then be used by airport planners and operators to estimate the qualitative performance based on traffic counts at intersections. The traffic counts can be put in the MLR model to estimate the total, platoon and forthcoming intersection delay, which results into an estimated

Table 1: Vehicle input parameters VISSIM-model

Type of Vehicle	Length (m)	Speed (km/h)	Accel./decel. profile	Share (%)
Passenger car	4.5	30	Car (default VISSIM)	10.0%
Airport bus	13.0	30	Heavy vehicle	4.8%
Catering truck	10.0	30	Heavy vehicle	17.2%
Fuel truck	12.0	25	Heavy vehicle	7.7%
Cleaning van	5.0	30	Light vehicle	7.7%
Toilet/water truck	8.0	30	Heavy vehicle	15.3%
Baggage train	20.5	15	Airport train	15.3%
Cargo train	20.5	15	Airport train	3.8%
Push-back tractor	8.0	15	Heavy vehicle	7.7%
Belt loader	7.0	15	Heavy vehicle	9.6%
High loader	11.0	15	Heavy vehicle	1.9%

Table 2: Level of Service criteria intersection delay for each infrastructure component, [5]

Level of Service	4-way prio. [s/vehicle]	4-way round. [s/vehicle]	3-way prio. [s/vehicle]	3-way alt. [s/vehicle]	Main road [s/vehicle/stand]
A	0 - 10	0 - 10	0 - 8	0 - 8	0 - 5
B	10 - 15	10 - 15	8 - 13	8 - 13	5 - 10
C	15 - 25	15 - 25	13 - 23	13 - 23	10 - 20
D	25 - 35	25 - 35	23 - 33	23 - 33	20 - 30
E	35 - 50	35 - 50	33 - 48	33 - 48	30 - 45
F	>50	>50	>48	>48	>45
F	$V_j > CAP_j$	$V_j > CAP_j$	$V_j > CAP_j$	$V_j > CAP_j$	$V_j > CAP_j$

performance expressed in LoS.

The service road performance is measured under four traffic compositions. The base composition is used once more, along with two compositions that distinctly represent each vehicle type. The inverse of the base composition is selected to depict significantly different traffic conditions, while another composition is chosen that equally represents each vehicle type. Lastly, a stress test is performed by applying a passenger car only composition. By testing these four compositions, it validates that the MLR model is insensitive to changes in the traffic composition, which makes the performance estimation applicable to various airport systems.

Results

Experimental setup

To obtain the PCU values, passenger cars are added to the base traffic composition for the following analysis. Additionally, multiple scenarios are created for each component-level VISSIM model. In each scenario, the number of vehicles of one of the vehicle types is increased by 25% of the total share to capture the impact of the vehicles on traffic performance. This process is repeated for different traffic volumes, which is increased by 150 vehicles per hour spread across the different directions. For each simulation run, the number of vehicles of each type (11 in total) and the total delay are collected from VISSIM.

Each run is simulated with a data-collection period of 3600 seconds (1 hour). This duration is ideal as it captures peak traffic variations and provides sufficient data for accurate performance analysis. A warm-up period of 3 minutes is installed, so that vehicles have time to occupy the model to a stable and representative level. Each scenario is simulated 10 times to obtain reliable and accurate results. This is because vehicles are generated and distributed (route-choice) stochastically, meaning that each model results in unique results.

Passenger Car Unit estimations

The MLR analysis provided PCU values for different airside service vehicles across various infrastructure components. The results demonstrate significant variation in PCU values depending on vehicle type and roadway configuration. Table 3 presents the estimated PCU values for each service vehicle type across the different infrastructure components.

The results indicate that slower vehicles, such as baggage trains and high loaders, exhibit higher PCU values due to their disproportionate contribution to traffic delay. These vehicles tend to accelerate and decelerate more gradually, which creates longer queue discharge times and amplifies delays at intersections.

Table 3: Passenger Car Unit for all vehicles and infrastructure components

Vehicle type	4-way prio.	4-way round.	3-way prio.	3-way alt.	Main road
Car (reference)	1.00	1.00	1.00	1.00	1.00
Bus	2.35	1.66	1.71	1.74	1.45
Catering truck	2.23	1.60	1.80	1.92	1.35
Fuel truck	2.63	1.67	1.85	1.75	1.67
Cleaning van	1.52	1.04	1.32	1.33	1.05
Toilet/water truck	2.38	1.48	1.80	1.70	1.21
Baggage train	3.53	2.29	2.61	2.51	2.20
Cargo train	3.67	2.33	2.70	2.48	2.21
Push-back tractor	2.14	1.31	1.61	1.63	1.95
Belt loader	2.45	1.29	1.59	1.51	1.65
High loader	2.94	1.53	2.26	2.08	1.89
Avg. (excl. Car)	**2.44**	**1.56**	**1.84**	**1.79**	**1.60**

Their reduced manoeuvrability means that the likelihood of finding a gap to merge or cross at the intersection is reduced compared to passenger cars, which means that their presence reduces the overall traffic flow. Additionally, the significant footprint of vehicles such as baggage trains and fuel trucks further impedes traffic flow, as they occupy more space on the road. This is also reflected in the results.

The results also show that the effects of speed, manoeuvrability and footprint are consistent across the different infrastructure components, meaning that the ranking in terms of PCU is roughly the same for entire service roads. However, the exact impact expressed in PCU of any vehicle compared to passenger cars differs for all infrastructure components. Table 3 indicates that the four-way priority intersection has the highest average PCU values. The service vehicles have a more noticeable impact on traffic flow on four-way priority intersections. This indicates that this type of intersection is less capable of facilitating smooth traffic flow compared to its counterparts. The results of the four-way roundabouts on the other hand, show that this component is much more indifferent to larger and slower vehicles, indicating its potential value for service road networks.

Comparing both three-way configurations highlights that these infrastructure components provide similar PCU values. Lastly, main roads have slightly lower PCU values compared to three-way priority intersections. This is interesting to note, since main road segments are effectively multiple closely positioned three-way priority intersections, with each intersection having an influence on delays upstream and downstream. This influence is also observed in the results of this analysis, since PCU values for the main road are 15% lower on average.

Service road performance

The capacities of the service road components expressed in PCU per hour are presented in Table 4. The results are divided between the four different traffic compositions that are presented.

The results indicate that the capacity is consistent across the three traffic compositions that include all service vehicles. The largest difference observed is between the “Base case" composition and “Inverted" composition at main road segments, with a deviation of 11.0%. The maximum difference across these three compositions is substantially smaller for the other infrastructure components, with a deviation of only 0.8%, 1.6%, 0.6%, 1.7% for four-way priority, four-way roundabout, three-way priority and three-way alternative intersections respectively.

However, the “passenger car only" composition results in significantly higher capacities at the four-way roundabout, three-way alternative intersection, and main road segments. These results indicate that the applicability of the MLR model is bounded, since the deployment of only passenger cars finds inconsistencies in terms of capacity expressed in PCU per hour. Nevertheless, despite significant variations in representative traffic mixes typically found on airport service roads, the capacities remain consistent. This highlights that the MLR model is capable of estimating the performance for more representative compositions. For that reason, the average output of the “base case", “equal" and “inverted" traffic compositions is used to determine the performance of service roads in further analyses, while appropriately capturing small deviations between these three compositions.

It is important to note that the capacities expressed in PCU per hour in Table 4 cannot be directly compared with each other, since this capacity is impacted by the estimated PCU values from the MLR model. These were found to be not consistent across the dif-

Table 4: Capacity (PCU/hour) for all composition scenarios

Composition	4-way prio.	4-way round.	3-way prio.	3-way alt.	Main road
Base case	2043.50	1561.56	1669.19	1338.55	1288.12
Equal	2050.23	1556.31	1653.57	1328.52	1351.70
Inverted	2061.10	1536.99	1658.45	1316.78	1430.58
Passenger car only	1925.00	3088.00	1837.00	2049.00	2041.00
Avg. (excl. Car only)	**2051.61**	**1551.62**	**1660.40**	**1327.95**	**1356.80**

ferent infrastructure components, which means that a generalisation of the capacity in terms of PCU per hour cannot be made. For this reason, Figure 4 has been created. This creates an overview of the absolute capacity in terms of vehicles per hour instead of PCU per hour.

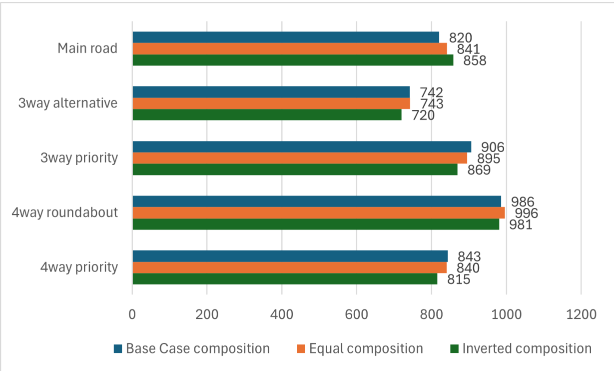

Figure 4: Capacity (vehicles/hour) for representative traffic compositions

The capacities expressed in vehicles per hour can be used to compare the performance of the infrastructure components. This validates that the four-way roundabout indeed facilitates the highest number of vehicle movements, with an average of 998.7 vehicles per hour. The three-way priority intersection comes second with 890.0 vehicles per hour, but serves one less traffic direction. The capacity of a four-way priority intersection (839.7 vehicles per hour) is significantly less than its four-way counterpart. Main roads have a reduced throughput compared to three-way priority intersections, highlighting the influence of multiple intersections on the traffic flow. Lastly, the three-way alternative, despite its similar PCU values as three-way priority presented in Table 3, performs notably worse with an average capacity of 735.0 vehicles per hour.

Table 5 presents the resulting LoS boundaries based on traffic compositions “base case", “equal" and “inverted". In this overview, the LoS criteria presented in Table 2 have been converted to LoS boundaries expressed in PCU per hour, based on the MLR delay prediction model presented in this research.

This analysis clearly demonstrates the exponential relationship between PCU and delay. For example, LoS “B" at four-way priority intersections has a interval length of 109 PCU per hour according to the MLR model, which is translated to 10-15 seconds of intersection delay. Conversely, LoS “E", which has 35-50 seconds of intersection delay, has approximately the same interval length according to the MLR model (114 PCU per hour), while the delay interval is three times as long (15 seconds instead of 5 seconds).

Furthermore, inserting the results of the capacity analysis reveals that certain infrastructure components reach capacity when the delay is less than the highest delay boundary at LoS “F". This is the case at the three-way alternative intersection and main road segments. What this effectively means is that the delay corresponding with service level “E" (and also “D" for main road segments) cannot be achieved, because the components have reached the pre-determined capacity. This is the additional criterion that the HCM has described [5]. In other words, this criterion ensures that the volume in PCU per hour corresponding with the estimated delay from the MLR model does not surpassess the maximum measured throughput.

Level of Service boundary validation The use of the LoS boundaries are tested on a network-level model, which is subjected to a larger degree of variability due to the stochastic processes of route-choice and vehicle generation. This test validates the robustness of the LoS boundaries and is therefore critical for demonstrating the added value this method provides for airport operators and planners. This analysis tests the robustness and accuracy by comparing the predicted LoS using MLR models with the LoS indicated by PCU per hour boundaries across various traffic compositions. The results are reported in Table 6.

The network model represents a service road of a pier-configured terminal building with 28 aircraft stands, which has an estimated yearly passenger throughput of 12-15 million passengers. The network consists of two four-way priority intersections, two four-way roundabouts, three three-way priority intersections, three three-way alternative intersections and four main road segments.

This analysis has shown a 99.3% accuracy for all intersections. Since each main road has multiple intersections depending on the number of aircraft

Table 5: Level of Service boundaries all infrastructure components

LoS	4-way prio.	4-way round.	3-way prio.	3-way alt.	Main road
A	<1305	<991	<1114	<1054	<1110
B	1305 - 1414	991 - 1087	1114 - 1212	1054 - 1154	1110 - 1239
C	1414 - 1561	1087 - 1216	1212 - 1340	1154 - 1285	1239 - 1357 (CAP)
D	1561 - 1662	1216 - 1307	1340 - 1430	1285 - 1328 (CAP)	N/A
E	1662 - 1776	1307 - 1409	1430 - 1531	N/A	N/A
F	>1776	>1409	>1531	>1328 (CAP)	>1357 (CAP)

Table 6: Results LoS boundary validation, All nodes and excluding main road nodes, Reference +100% scenario

	All nodes		**Excl. Main Road**	
Inside boundaries?	Counts	Percentage	Counts	Percentage
Yes	4601	99.3%	1361	97.8%
No	31	0.7%	31	2.2%

stands, the results are also presented excluding these intersections to prevent the main roads from disproportionately affecting the accuracy. Furthermore, the simulations have found that each main road intersection is classified as LoS “A". Even when excluding these, the accuracy remains 97.8%. This indicates that the LoS boundaries are suitable for airport applications, allowing for the estimation of intersection LoS based on PCU flows.

Discussion

Key findings and interpretation

The study delved into the intricacies of traffic heterogeneity, particularly focusing on service vehicles with various speed profiles, and their unique acceleration and deceleration characteristics. By employing PCU values, this research was able to capture these differences, uncovering significant variations across various infrastructure components.

One of the standout observations concerned the efficiency of different intersection types. Four-way priority intersections exhibited higher PCU values compared to four-way roundabouts. This finding suggests that roundabouts are more adept at handling service vehicles, making them less sensitive to the diverse traffic conditions. Under more traditional roadway conditions, it has also been found that roundabouts provide lower delays compared to other unsignalised intersections [24], especially under high traffic conditions [25]. Similarly, both types of three-way intersections demonstrated relatively low PCU values, indicating that delays are less severe at identical vehicle volumes compared to four-way priority intersections.

Existing literature often emphasises comparing methods for determining PCU values and refining these methodologies [6, 26, 27]. However, little attention has been given to the differences in PCU values between various intersection types. This study underscored the necessity of determining PCU values for individual components, especially in heterogeneous traffic conditions prevalent on roadway systems such as service roads. This also means that comparing PCU values for different infrastructure components with existing literature is challenging, as generalisations are often made for the impact of any vehicle class across entire roadway systems, as shown by research on PCU estimation for signalized intersections in India [28].

In terms of capacity analysis, the study found that capacity, expressed in PCU per hour, remained largely consistent across different traffic compositions. However, variations became apparent under extreme or unrealistic conditions. This indicates that while the PCU-based approach provides a reliable estimate for normal operations, it may not be able to estimate the performance to the highest accuracy under every condition.

The component-level LoS analysis established LoS boundaries for different service road infrastructure components, expressed in PCU per hour. These boundaries allow airports to estimate the LoS of individual infrastructure components based on current traffic volumes. Research on comparing methods for determining the LoS of roadways [29] indicates a potential for determining the LoS based on the volume-to-capacity ratio. The boundaries expressed in PCU per hour in this study effectively replicate this method, but a more complex and analytical approach is applied to account for traffic heterogeneity using MLR. Also, instead of considering a fixed volume-to-capacity ratio for all components, this research distinguishes each infrastructure component based on estimated delays from MLR models. Testing the LoS boundaries on a network model has found an accuracy of 97.8% for all intersections considered in this research, by comparing the results of the LoS estimation using the boundaries with the estimated LoS based on MLR.

Implications

Scientific This research provides valuable insights into roadway performance under heterogeneous traffic conditions, particularly on airport service roads where a diverse mix of vehicles with varying performance parameters and speeds is present. The study demonstrates that PCU values are effective in capturing traffic heterogeneity, even in highly diverse conditions. By using MLR, the research identified PCU values for eleven different service vehicles, revealing that their performance relative to passenger cars depends significantly on the type of intersection. This finding suggests that generalising the PCU value of a vehicle type across the entire network is not advisable. Instead, distinctions should be made between different infrastructure components according to this research. Additionally, the study successfully applied the principles of the HCM to service roads, which shows the potential for qualitative assessment of service road performance using a LoS scale. Even under significantly more heterogeneous traffic conditions, the HCM could successfully be applied, using PCU values that capture the varying traffic mix.

Practical For practical applications, this research offers a method for determining the LoS of service roads that is both accessible and applicable to various airport environments. Airports can now evaluate the performance of individual infrastructure components based on traffic counts, which can be converted into hourly PCU flows using the PCU values identified in the study. The findings indicate that roundabouts should be preferred over four-legged priority intersections at critical points due to their higher efficiency and lower sensitivity to traffic heterogeneity. Three-way alternative intersections perform considerably worse compared to three-way priority intersections. Considerations regarding possible aircraft taxiing conflicts should however still be made when choosing between the two three-way intersection configurations. Main road segments with multiple aircraft stands (i.e. intersections) must be analysed as a collective infrastructure component, since the performance of individual intersections is significantly influenced by closely spaced intersections upstream and downstream.

Limitations

One key limitation is the omission of interaction effects between different vehicle types in the MLR model used to determine PCU values. This exclusion means the model may not fully capture how the presence of one vehicle type influences the delay effects of another, potentially affecting the accuracy of the derived PCU values. To address this, a simplified VISSIM model was created to account for these delay effects.

Additionally, while the study analysed various vehicle types, it assumed fixed physical and behavioural parameters for service vehicles. In reality, these parameters can vary due to external factors, impacting the determination of PCU values and their practical application.

Simplifications were also made in modelling main road segments, which were analysed using a VISSIM model with three aircraft stands. The findings were generalised, but variations in segment length, number of stands, and distance between stands were not fully considered, which potentially limits the validity of the results.

Roadway performance analyses showed consistent results across typical airport traffic compositions, but the LoS boundaries are not universally applicable to all traffic mixes. A stress-test with "passenger car only" traffic revealed significant inconsistencies, though this composition is uncommon on service roads. Additional validation on the network-level model with varied vehicle mixes achieved high accuracy, proving the robustness of the PCU values and LoS boundaries under varying conditions.

Recommendations for future research

Firstly, as a simulation-based study, the results have yet to be validated with real-life data, which is currently lacking because airports have not prioritised analysing traffic performance on service roads [12]. Validating the study's methodology with observations from critical bottlenecks at airport service roads would be beneficial, allowing for further calibration of PCU values and performance measures.

Additionally, the applicability of this research is limited to the five critical infrastructure components studied, and variations of these configurations exist. Traffic engineering expertise is needed to assess how these variations, such as stop signs, three-way or five-way roundabouts, or uncontrolled intersections, impact performance. Replicating the methodology of this research might be needed to estimate the performance of intersection variations.

Further improvements in estimating the LoS of service roads can be achieved by considering different turning rates at intersections, which were not included in this study. Varying turning rates result in different degrees of conflicting flows, affecting intersection performance and capacity. The study used reasonable and typical turning rates for all analyses.

This analysis represents a first step towards evaluating the performance of service roads, which can be utilised in future traffic management and network performance optimisation. A valuable recommendation is to incorporate traffic performance into the optimisation objective of the gate assignment problem at service road-congested airports. This approach will not only optimise the operational utilisation of the gates but also improve traffic conditions as a secondary objective of the gate assignment problem by, for example, spreading out the assignment of the gates spatially and temporally.

Conclusions

This research concluded that the performance of individual airside service road infrastructure components can be effectively determined through a combination of PCU analysis, capacity estimation, and LoS assessment. The study highlighted the significant impact of traffic heterogeneity on infrastructure performance, emphasising the importance of converting vehicle flows into standardised PCU flows. Using a combined approach of microscopic traffic simulation and MLR, it was found that PCU values varied considerably across different intersection types, indicating that the performance of service vehicles relative to passenger cars depends on the intersection type.

The performance analysis revealed that, despite higher PCU values, four-way priority intersections maintained competitive throughput compared to other intersections. However, service vehicles were more negatively impacted relative to passenger cars, resulting in higher PCU values. Conversely, roundabouts showed more stable performance and accommodated service traffic more efficiently. The implementation of three-way alternative intersections at critical network locations posed operational challenges due to their limited overall capacity. Establishing LoS boundaries in PCU per hour allowed for a clear evaluation of individual infrastructure component performance, making the method accessible for various airport service roads.

This research presents a standardised, widely applicable method for estimating the performance of airside service roads across various airport environments. The methodology combines PCU-based traffic modelling, capacity estimation, and LoS determination, offering a comprehensive framework for assessing service road performance at both component and network levels. The findings indicate that PCU values must be calculated for each infrastructure type, as they vary significantly between different intersections. While LoS thresholds remain relatively stable, minor discrepancies due to traffic composition variations need to be considered. The methodology's validation on a representative network confirms its broader applicability, making it a valuable tool for airport planners and engineers aiming to optimise airside traffic management.

The standardised method developed in this study bridges the gap between traditional traffic engineering approaches and the unique operational challenges of airside service roads. It provides a data-driven foundation for future infrastructure planning and ensures that airports can evaluate and optimise service road networks in response to growing operational demands.

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