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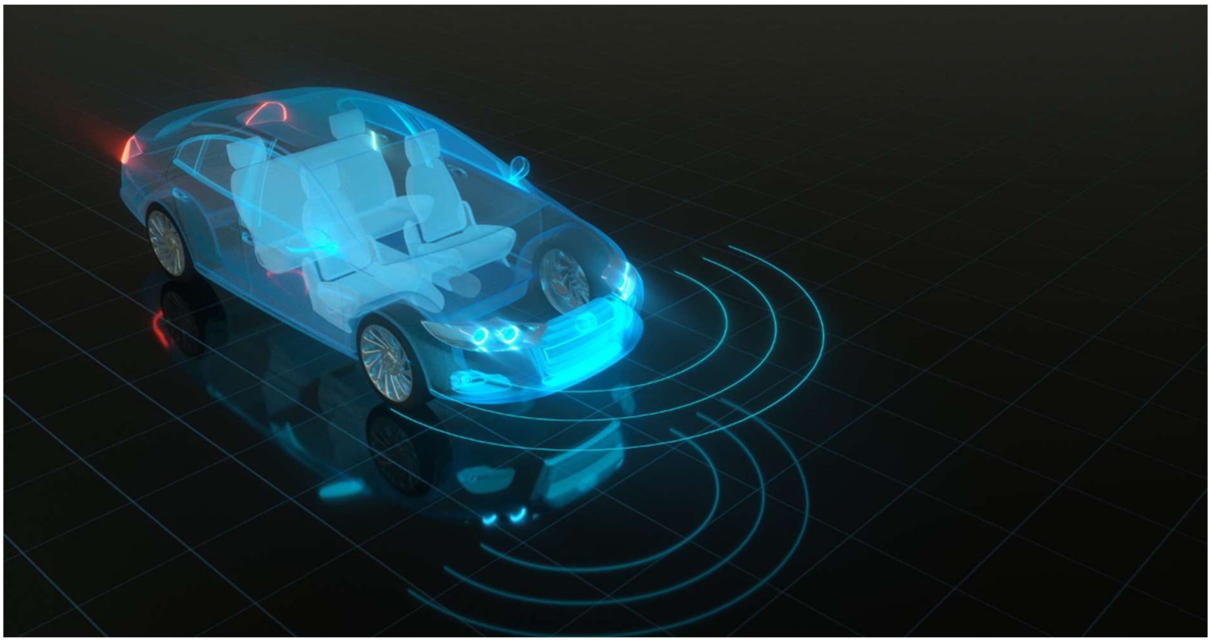

Impacts of AVs on the Capacity of a Dutch Roundabout

BACHELOR'S THESIS

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Impacts of AVs on the Capacity of a Dutch Roundabout

How different Autonomous Vehicle Types and their Penetration Rates impact the capacity of a Dutch Roundabout

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Preface

The report “Impacts of AVs on the Capacity of a Dutch Roundabout” was written by me for the department Verkeersmanagement en -Prognoses of Goudappel from May to July of 2024. It is my Bachelor’s thesis for the programme Civil Engineering at the University of Twente.

I want to thank Goudappel for giving me the opportunity to come to their company and directly learn from their traffic engineers. I want to especially thank my external supervisor Mark van den Bos, who helped me immensely with my thesis, as well as the proposal thereof. During my stay he was extremely busy, but every time I walked into his office, he made time for me. I also want to thank my internal supervisor who was equally as busy, but every meeting via Teams, he gave me insightful tips and ideas that would further improve my research.

I also want to thank the people at the VMP department making me feel welcome. And the people that I sat with in the ‘stilteruimte’, while I had hearing issues due to an ear infection.

The last people that I want to thank are my family and especially my little sister Evi Geerlings, for scanning my thesis and coming up with more information, ideas, and feedback.

If there are any questions concerning this research, you can contact me via k.h.geerlings@student.utwente.nl.

Kai Geerlings

18th of July, 2024

Summary

The main goal of this report is to research the impacts of autonomous vehicles (AVs) on the capacity of a Dutch roundabout. This was done by answering the sub-questions; How can driving behaviour of AVs translate over to the micro-simulation model in Vissim; How to gather data from the roundabout model in Vissim to determine the capacity; What is the roundabout capacity with different AV types and AV penetration rate scenarios; What are the effects of pedestrian and cyclist crossings on the roundabout capacity.

Autonomous vehicles (AVs) labelled as level 4 and 5 by levels of driving automation have the possibility to change the current traffic infrastructure landscape. They can make transportation more efficient, safer and accessible for everyone. The Dutch Ministry of Infrastructure has become aware and is now adjusting regulations to make testing of AVs possible in the current traffic network. The effects of AVs need to be modelled and researched with modelling tools in advance for proper testing.

Literature review shows that the impact of AVs on the entry capacity of the roundabout depends on many variables. The geometrical aspects are important for currently existing linear regression models that use relationships between one dependent variable and multiple independent variables to estimate the capacity of roundabouts. Linear regression models are based on empirical data, and since AVs are not existing in the current traffic environment it is not possible to use this method. Another method is gap acceptance modelling. It uses the critical gap, follow-on headway and circulating traffic parameters, such models are based on assumptions, variables and distributions based on the current traffic network. How AVs will perform on roundabouts is still unclear and therefore a different method was used.

Vissim is a microsimulation model software package that can model any traffic situation and change almost all variables and their distributions, as well as geometrical elements of road design elements. For this research the geometrical elements have been based on Goudappel and CROW standards. The capacity of a roundabout is hard to determine due to the many variables at play. Therefore, a smaller approach was taken where only one entry leg was observed. Meaning that the term capacity for this report means entry capacity of the roundabout.

Vehicle behaviour is dependent on many variables. Therefore, three different AV types have been considered, cautious, normal and aggressive AVs. These behaviour types are based on how aggressive they are in their behaviour as their name implies. Cautious AVs drive more cautiously than conventional vehicles (CVs), while normal AVs are equivalent to CVs, and aggressive AVs drive more aggressive than CVs. AVs are expected to have the same behaviour variables as CVs, but without some of the human error-based parameters. The AV behaviour types can be translated to Vissim using the car following model Wiedemann 99 parameters. Next to car following, the roundabout entry behaviour is also important. This is mostly based on time gaps and minimum clearances, which differ for every vehicle type.

To find the influence of these different AV types, multiple scenarios were created and simulated. The scenarios were based on three different ratios regarding entry and opposing traffic flows, five AV penetration rates from 20% to 100% in increments of 20%, and four additional scenarios based on the presence of pedestrians and cyclists. Cautious AVs caused drops in capacity, while normal AVs were comparable to CVs. Aggressive AVs caused the highest increases in capacity as expected. The ratio of 25/75 had the most varying results, as cautious vehicles caused a decrease in capacity of 20%. When pedestrians and cyclists were involved, a further drop was observed to a capacity decrease of 26%. While Aggressive AVs had an increase of 21% at 100% penetration rate. Overall, the increase in the level of aggressiveness, as well as penetration rate and lack of pedestrians and cyclists led to an increase in capacity.

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Nomenclature

In this chapter abbreviations, symbols and terms are explained. Table 1 shows the list of abbreviations used in this report. Table 2 shows the list of units used in this report, except from design elements, as they are explained in their respective chapters. And as for terms mainly an explanation is necessary for 'capacity'. Since the term capacity is used commonly in this report as the entry leg capacity of a roundabout.

Table 1: List of abbrevations.

Abbreviation	*Description*
CV	Conventional vehicles
AV	Autonomous vehicles
HGV	Freight traffic
OD-Matrix	Origin/destination matrix

Table 2: List of units.

Unit	*Description*
m/s^2	Meter per second squared
%	Percent
Veh/h	Vehicles per hour
min	Minute
h	Hour
s	Second

1. Introduction

Autonomous vehicles (AVs) are expected to revolutionize many types of sectors that require transportation. It can make transportation a lot safer, efficient, as well as accessible for everyone. However, this potential also makes it harder to use AVs. Due to influencing many different sectors and people, it faces a lot of problems dealing with regulations, public acceptance, and safety concerns.

The Netherlands has become aware of the potential of AVs, and investments in the autonomous vehicles sector have been made. During the last three decades multiple start-ups surrounding the AV sector have been founded trying to further develop AVs (Tracxn, 2024). There was also a realization that the well organised, structured, and maintained infrastructure in the Netherlands can be used as the perfect testing environment of AVs.

Therefore, around 2015, legislation was changed such that testing of AVs in the Netherlands was made possible (RDW, 2024). The Ministry of Infrastructure and Water Management stated that they strive towards a future with AVs, as they will reduce the number of accidents attributed to human error, reduce fuel usage and lower emissions, as well as reducing tailbacks.

While the Ministry of Infrastructure and Water Management note that fully autonomous vehicles are still in development and the focus is more on self-driving functions such as, adaptive cruise control, brake assistance, video cameras, recognizing other road users. While the Dutch infrastructure is very well suited for testing AVs as conflict points are reduced as much as possible, roundabouts might be a challenge for AVs with the large amount of conflict points in a short time span. Since many types of road users intersect on a Dutch roundabout, a normal single-lane roundabout has 4 conflict points whereas a Dutch roundabout with cyclist and pedestrian facilities has 24 points of conflict. A normal intersection without these facilities also has 24 points of conflict. However, these can be bypassed with well-programmed traffic signals. A roundabout does not have these, and an AV would have to traverse through multiple 'active' conflict points. There are many types of roundabouts, and they are all an integral part of the Dutch traffic infrastructure, according to DTV there are roughly 5900 roundabouts in the Netherlands. Roundabouts provide a very safe and efficient way to integrate different means of transport in one intersection.

This report will go into more detail how AVs would have an impact on the capacity of a Dutch four-way entry roundabout.

2. Context

This chapter is about Goudappel that has commissioned this research assignment and the study 'area'. The study area, in this case a standard Dutch single-lane roundabout.

2.1. Goudappel

Goudappel provided the opportunity to start this research assignment as they are a consultancy firm in the mobility planning sector. Goudappel wants to create a more sustainable transport system for everyone, and they provide the Dutch Government, Municipalities, and Cities with decision making data and consultancy services.

This research assignment will be useful to Goudappel to integrate AVs in their projects, if necessary, regarding roundabout intersections. Although predictions surrounding timeframe and the penetration rate of AVs in the transport sector are very rough, estimations can be made and used. There are different types of AVs, which might also have different impacts on capacity of certain road sections. That is why Goudappel wants to research this effect and this research assignment is about finding the impact of different types of AVs on the capacity of a Dutch four-way entry roundabout in different AV penetration scenarios.

2.2. Dutch Single-lane Roundabout

In this chapter the study 'area' will be discussed. The study area in this assignment is a four-way single-lane entry roundabout located in the Netherlands. However, this is going to be in a test environment where the roundabout will be tested for multiple scenarios. The scenarios are based on pedestrian and cyclist facilities, major and minor traffic flow, AV penetration rates, and AV types. The AV types are based on differences in AV behaviour.

Roundabouts generally have less points of conflict than normal intersections. Points of conflict are classified as locations where paths of road users intersect. A single lane roundabout with four entry legs has four vehicle to vehicle conflict points. If the roundabout has pedestrian and cyclist facilities the roundabout has 16 additional lateral points of conflict. These lateral points of conflicts are between vehicles and cyclists (eight points) as well as vehicles to pedestrians (eight points). Since the vehicles will have to slow down or even come to a halt before these crossings an additional 4 points of conflict between vehicles to vehicles must be taken into account. Adding up to a total of 24 points of conflict, this is equal to a four-legged intersection without any pedestrian or cyclist facilities.

2.2.1. Roundabout Safety

The design of a roundabout is very important, as it can influence its safety, capacity, and overall functionality. In the Netherlands roundabouts located within the city are in most cases equipped with bicycle paths and pedestrian crossings. This means that apart from the circular carriageway it also has two additional circular 'paths', these two are the aforementioned bicycle path and pedestrian crossing. While there are many variations of roundabouts, where pedestrian crossings have been omitted, or bicycle paths have been incorporated in the circular carriageway becoming a bicycle lane. Cyclists are generally safer when using roundabouts rather than using normal intersections with bicycle facilities (SWOV, 2022). For pedestrians the difference in safety between normal intersections and roundabouts is hard to determine as the total amount of deaths due to crashes between vehicles and pedestrians is low for both types of intersections and further detailed data regarding accidents is not available.

2.2.2. Design Elements

The design of roundabout is the subject of several guidelines around the world. In the "Roundabouts – Application and design" manual issued by the Ministry of Transport, Public works and Water management of the Netherlands, details regarding the design and types of a single-lane roundabout are specified.

There are several design elements that have important functions in a roundabout. First of all, the 'legs' connected to the roundabout. It is important that these are connected to the roundabout radially, see Figure 1. Any offset would result in reduced entry deflection. Entry deflection means that cars have to reduce their speed to enter the roundabout. An increase in entry deflection has positive impacts on reducing crashes between circulating and entering traffic. The optimal angle for entry deflection is 90 degrees. The reduction in speed also allows pedestrians and cyclists to have a more comfortable crossing opportunity.

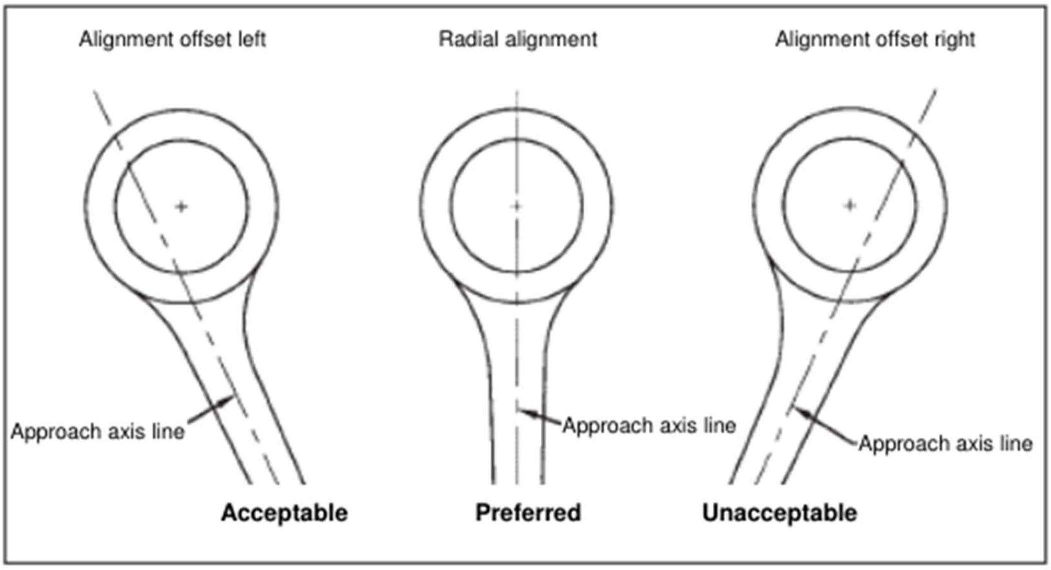


Figure 1: Entry 'leg' axis in relation to the centre of the roundabout (Royal Haskoning; DHV, 2009).

To ensure entry legs approach the roundabout without any offset, radial connection splitter islands are used. While there are three types of splitter islands (see Figure 2), not all three of them offer optimal approaches. Tangential connections approach the roundabout tangentially and thus does not use the 90 degrees rule for optimal entry deflection. The last type is the mixed version of the previously mentioned types. The approach is curved such that it meets the circular road tangentially.

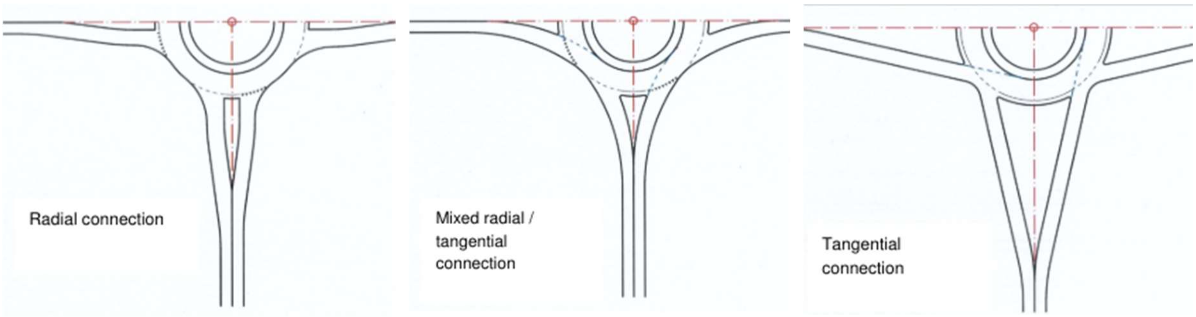


Figure 2: Splitter Island types (Royal Haskoning; DHV, 2009).

Splitter islands are also used to facilitate bicycle paths and pedestrian crossings. As mentioned before splitting islands and radial connection type roundabouts have speed reducing effects. Thus, decreasing the gap in speed between different the different roundabout users. The lateral conflict from cyclists and pedestrians with vehicles will therefore not be as severe. Next to that, splitter islands act as refuge points, although this is mainly used by pedestrians, both cyclists and pedestrians can rest here and judge if it is possible to cross the road. In most cases roundabouts give cyclists priority and although this is not safer than letting the vehicles have priority. It is recommended that cyclists are given priority in urban areas based on the balancing of safety, comfort, and cyclist traffic flow (SWOV, 2022). Cyclist and pedestrian facilities are not taken into consideration for the inner and outer radius of the roundabout. They are separated, and in most cases, they are designed to be one vehicle length approximately 5m to 6m away from the give way line.

Next to the previously mentioned design elements Table 3 contains dimensions that are generally recommended for a single lane roundabout. The outer radius is from the centre of the roundabout to the outer pavement edge of the roundabout. The inner radius includes the central island and the overrun area. Where the overrun area is used by longer vehicles such as larger trucks to get past the roundabout, it is sloped with a maximum height different of 0.05m. To make sure that normal vehicles do not use it. The circulating lane is the difference between the outer and inner radius. The entry angle can range from 80 degrees to 110 degrees but is preferably 90 degrees as it is the optimal entry angle regarding the entry deflection. The entry and exit radii are best to be kept as small as possible due to larger radii making it easier to enter and exit the roundabout with higher speeds, making it unsafe. The lane width of both entry and exit lanes have close to no impact on circulating speeds, but very wide lanes can promote unwanted faster entry and exit speeds.

Table 3: Design elements and their dimensions (Royal Haskoning; DHV, 2009).

Design Element	Standard (m)
Outer radius (Rbu)	18.00
Inner radius (Rbi)	12.75
Circulating lane width (B)	5.25
Overrun area	1.50
Entry curve radius (Rt)	8.00/12.00*
Exit curve radius (Ra)	12.00/15.00*
Entry lane width (Bt)	4.00/3.50*
Exit lane width (Ba)	4.50/4.00*
Splitter island width (Bm)	3.00
Splitter island length (Lm)	10.00-15.00
***Without splitter/with splitter**	

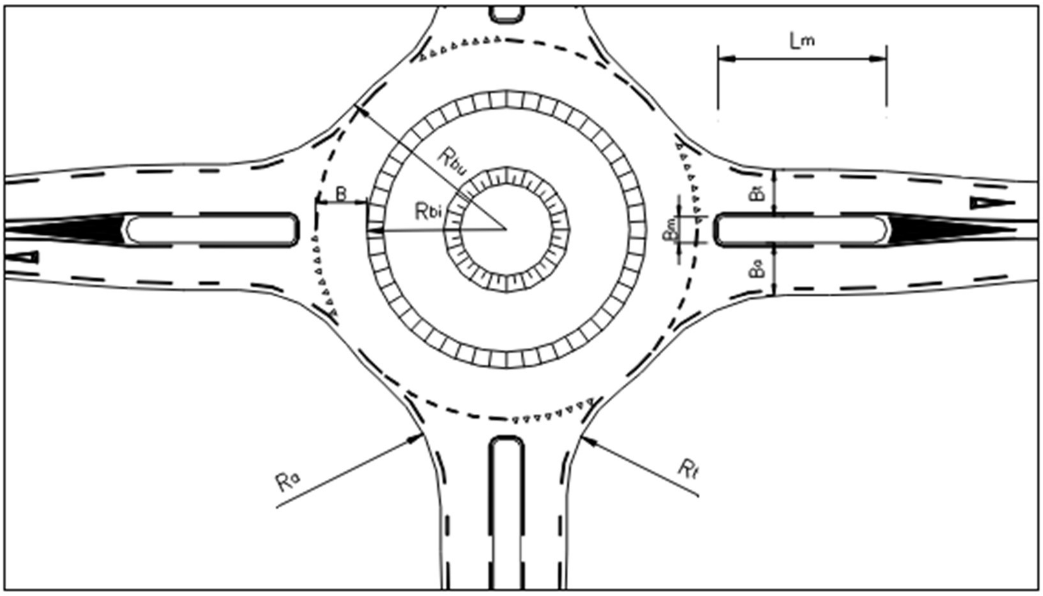


Figure 3: Design elements single lane roundabout (Royal Haskoning; DHV, 2009).

3. The Problem

This chapter contains information about the problem. The problem will then be reduced to a small part, to fit the timeframe of this research assignment. This is further explained by introducing the scope. The previous three mentioned components will be used to create research questions.

3.1. Problem Statement

With the development and introduction of autonomous vehicles (AVs) and their introduction in the near future. AVs will slowly influence the current traffic network. The current assumption is that AVs will have a positive impact on the traffic flow and the capacity of the road network. However, their exact impacts are still uncertain. This is due the uncertainty of how AVs will behave on the road. The other uncertainty is related to their introduction period, before AVs have fully saturated the market, it is predicted that it will take a few decades. Therefore, the impact of AVs on the capacity of the road network will be tested for different AV types as well as different penetration rates, to research the transition period.

3.2. Problem Objective

The research objective is to test multiple AV behaviour types with different penetration rates on their impact on the maximum capacity of a standard Dutch four-way single-lane entry roundabout.

3.3. Scope

The research objective is a very small part of the overall problem. The overall problem states that the AV impact needs to be researched for the entire network, however for this research assignment only one specific roundabout type will be tested, a Dutch four-way single-lane entry roundabout with bicyclist and pedestrian facilities. These facilities will be pedestrian and bicyclist crossings separated from the circular vehicle lane.

In the introduction it has been suggested that there is a public concern regarding the safety of autonomic vehicles, however this will not be part of this research as it is only about the capacity.

While the future traffic network may also be influenced by future upcoming transport modes, only AVs will be considered, and it is assumed that the penetration rate of AVs can reach 100%. During testing the geometries of the roundabout will stay the same even when crossings for pedestrians and cyclists are added. These can be facilitated on the splitter islands.

The roundabout will only be tested for one entry leg, due to the many scenarios and factors playing a role in finding the maximum capacity of a roundabout. The factors that will be tested in this research project are different AV types based on driving behaviour, AV penetration rates, pedestrians, cyclists and if the entry leg is a major or minor traffic flow compared to the circulating traffic flow on the roundabout.

3.4. Research Questions

The main research question is directly related to the problem objective (Chapter 3.2) and can be answered using the results from the sub-questions that fall within the scope of the research assignment (Chapter 3.3).

Main research question: *What is the impact of different AV types and penetration rates on the entry leg capacity of a Dutch four-way entry single-lane roundabout?*

Sub-research questions:

1. *How can the driving behaviour of AVs translate over to Vissim?*
2. *How to gather data from a roundabout in Vissim to determine the capacity?*
3. *What is the roundabout capacity with different AV types and AV penetration rate scenarios?*
4. *What are the effects of pedestrian and cyclist crossings on the roundabout capacity?*

The main research objective is to find the impact of AVs on the capacity of a roundabout. As mentioned before this will be about the entry leg capacity. To determine this impact the microsimulation software Vissim will be used. The first two questions are related to Vissim, since the different types of AVs need to have their driving behaviour calibrated accordingly. When the modelling part is completed, the data required for the calculations of the capacity need to be gathered within Vissim. The other two questions are more related to the analysis of the data from Vissim. With the unpredictability of both the behaviour of AV types as well as the penetration rates of these AVs, different scenarios must be simulated. The capacity for these different scenarios can be calculated and analysed. In order to research the effects of Pedestrians and cyclists on the roundabout capacity the different AV types and penetrations rates also need to be tested with pedestrian and cyclist crossings ‘turned off’.

4. Theoretical Framework

This chapter will go into the theoretical framework for this research project based on literature, related studies, and expectations. The theoretical framework consists of information about AVs, roundabout capacity and research methods used to find the capacity.

4.1. Autonomous Vehicles

Autonomous vehicles are very new and still need to be researched in more detail. Especially how they will impact the capacity of certain road sections. In order to do this for the roundabout capacity, some uncertainties will have to be considered and will be talked about more in this chapter. Topics such as levels of automatic driving, types of AVs and penetration rates will be discussed.

4.1.1. Levels of Autonomous Driving

There are different levels of autonomous driving in the current state of AVs, not every vehicle can drive fully autonomous. Most cars currently have parts of an AV most commonly tools such as braking assistance and adaptive cruise control. While not every AV is allowed on the road legally in the current environment it is therefore important to distinguish between the different levels of automation.

In SAE International (2021) the different levels of autonomous driving have been summarized. There are currently six levels of automation from level zero to level five. At level 0, there is no automation at all, only the driver can influence the driving activities. At level 1, a driver can get assistance from the automatic systems such as Electronic Stability Control or Emergency Brake Assist. These can only be used to help the driver when necessary, driving must be done by the driver itself. At level 2, partial driving automation is allowed. The system can now influence driving, by controlling the steering wheel and the braking system. Level 2 still requires the driver to be analysing the situation when making use of these systems. Level 3 has conditional driving automation; the vehicle can drive without interventions from the driver in some limited situations. This still requires the driver to supervise the situation, since in emergency situations the driver must intervene manually (Wiseman, 2021). Levels 4 and 5 have full driving automation.

Wang et al. (2021) discussed the differences between levels 4 and 5. The main difference between the two levels is that level 4 still has a predefined operating range. It can only handle the situations within this operational design domain. However, level 5 has an operating range that is only limited by the ethical norm, it can operate in any situation. See Figure 4, for an overview of the six levels of driving automation.

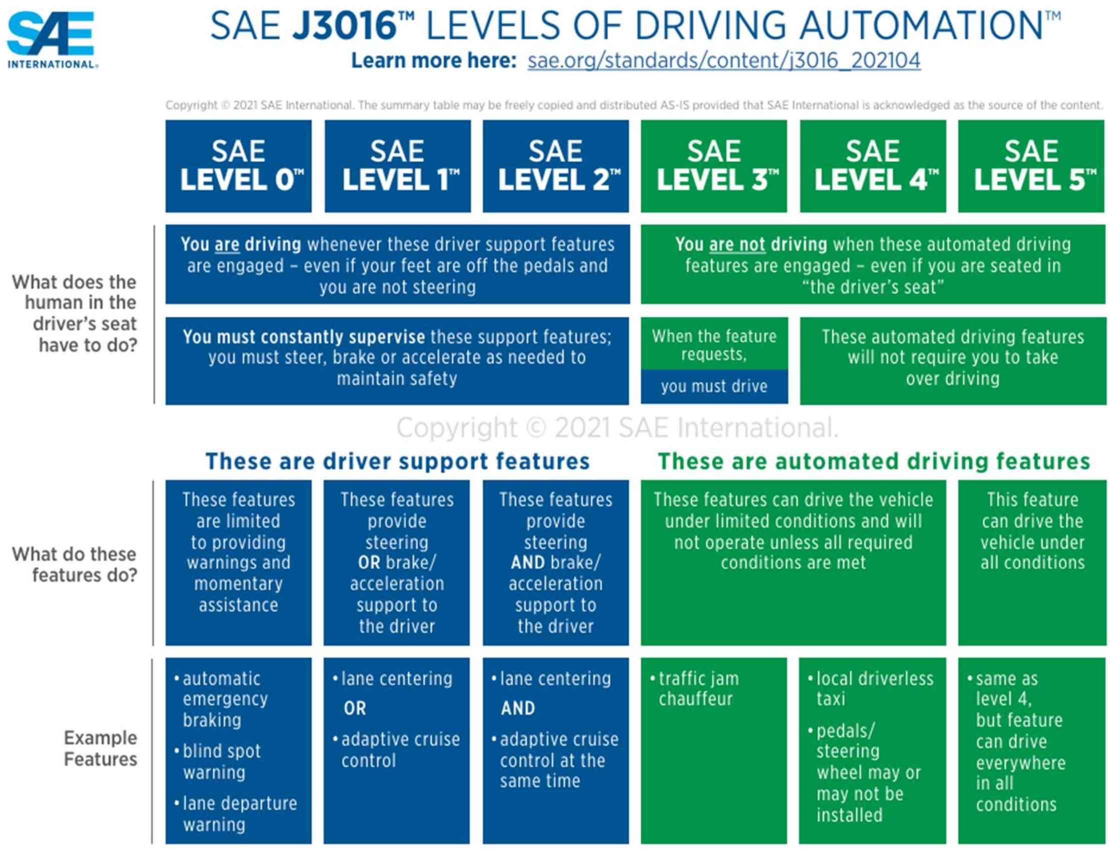


Figure 4: Levels of Driving Automation. (SAE International, 2021)

4.1.2. Types of Autonomous Vehicles

In order to handle the uncertainty of the behaviour of Autonomous vehicles. Types of autonomous vehicles can be determined and used to predict their impact on the capacity of the road network. Especially the introduction period of AVs or the transition period from human-driven cars to AVs has to be researched. This transition period will be discussed further in Chapter 4.1.3. In the research article written by Olstam et al. (2020) three approaches for modelling of the driving behaviour of automated vehicles were highlighted.

The first approach is to adjust the driving behaviour model parameters in the traffic simulation model, to fit the expected AV driving behaviour. The second approach replaces the driving behaviour model completely with new automated vehicle driving behaviour models. The third approach extends the second approach by including “nanoscopic” modelling of automated vehicles features.

For these approaches to be implemented further understanding of the levels of driving automation is needed. Therefore, two concepts are suggested to further specify the levels of driving behaviour in relation to the level of driving automation. As mentioned in Chapter 4.1.1, level 4 of driving automation is considered as mostly Autonomous. These two levels can be further specified in AV classes; Basic AV, Intermediate AV, and Advanced AV. Basic AVs are in SAE level 4 and can only be used in very controlled situations. The other active modes need to be physically separated; this makes their driving behaviour very cautious. Intermediate AVs are level 4 vehicles with some capabilities to handle different road environments and contexts. They are still cautious but can drive more offensively when met with the right scenarios. The last class is the advanced class, it can handle most road environments and contexts. While being offensive unless met with a complex scenario, where the advanced AV still has to be cautious. These three classes only envelopes SAE level 4, for level 5 another concept is used that also translates the previously mentioned AV classes to driving behaviours, the concept of driving logics. Driving logics are used to specify how a singular vehicle of a specific AV class behaves at a certain road section (Olstam, et al., 2020). There are four driving logics, where the first two are more related to the behaviour of the three AV classes, and the last two are related to level 5 AVs.

When a predefined path is determined, and the car follows this and only uses brakes to avoid collisions there is talk of Rail-safe logic. Cautious logic when gaps are calculated, and merges happen only if these gaps are acceptable. If it is in a complex scenario where it cannot fully comprehend the situation it will slow down like the Rail-safe logic. The Normal driving logic assumes that the AV can drive like a human with improved capabilities as it can process information faster than a human. The All-knowing logic is the perfect level 5 AV, as it communicates with other vehicles, has perfect perception, and uses both to predict the situation and adapt to it accordingly in order to get from one point to another as effectively as possible.

4.1.3. Penetration Levels

The penetration rate of AVs on the traffic network is very important. AVs behave differently from self-driven vehicles. While a complete transition from self-driven vehicles to autonomous vehicles might be wanted for safety and comfort reasons, this could take quite a while. It is therefore important that the transition period is going to be researched on how the mixed vehicle types will influence the capacity of road sections. Bilal and Giglio (2023) mentioned several penetration rate studies and results, which can be used as an incline for the future of AV penetration rates.

Ben-Haim et al. (2018) used a survey method, where both Israeli and International experts were asked about the penetration rate in two rounds. According to the results Israeli experts predict an AV penetration rate in the year 2050 between 60-70% and the international experts predict between 30-60%. Litman (2020) performed a theoretical analysis based on a lot of influential factors and predicts an AV penetration rate of 50-80% by 2060. Milakis et al. (2017) used a scenario analysis based on impactful technologies and policies for the implementation of AVs. The predicted AV penetration rate from this analysis is 61% by 2050. The difference in these predictions shows that an accurate prediction of the AV penetration rate is very hard, since it relies on so many factors.

4.2. Roundabout Capacity

The US Department of Transportation (2000) discusses the term capacity regarding roundabouts. They stated that the maximum rate at which vehicles can be expected to enter the circulating flow of the roundabout during a given time at usual road and geometrical conditions, is called the capacity. Meanwhile, the term total capacity of a roundabout is not used, due to it depending on too many factors (US Department of Transportation, 2000). Instead, the usage of the term entry capacity or approach capacity is the most useful and considered in similar types of research. In the case of Empirical or gap-acceptance models the entry capacity of a leg is directly calculated. However, micro-simulation software VISSIM outputs a lot of different data that can be used to analyse the situation. Therefore, it is important to know which data is important to look at.

In the case of a roundabout three output results can be used. The difference between the input and the output of the entrance lane (veh/h) is one of these. When the output is lower than the input it means there is a buildup of traffic on the entrance leg. The queue delay (s) is also an indication of a possible maximum capacity, if the queue delay is too high the vehicles cannot enter the circulating traffic flow on the roundabout. Meaning that the capacity in that specific situation has been reached. That means it is important to also test other intensity scenarios where the major flow is shifted from the entrance leg to the circulating flow. The queue length (m) is also an important indicator, if the queue length is too high it means that the roundabout cannot facilitate all the traffic coming from that specific entrance leg.

4.3. Roundabout Capacity Research Methods

The capacity in traffic flow terms is the maximum number of units that can traverse a traffic element per unit of time, which in most cases is labelled with the unit vehicles per hour (Veh/h). Intersections are implemented in different situations leading to specific parameters that change for every intersection unless they are standardized. In order to calculate the capacity of an intersection different types of capacity modelling methods have been developed. These three methods consist of Empirical modelling, Gap-acceptance models, and microsimulation (Yap, Gibson, & Waterson, 2013). The first two methods will be further discussed in this chapter, while microsimulation will be discussed in Chapter 4.4.

4.3.1. Linear Regression Modelling

A roundabout has many geometrical elements as described in chapter 2.2. It is therefore necessary to understand what type of influence every single geometrical element has on the capacity of a roundabout. Empirical capacity models are based on the relation between geometrical elements and measured capacity of existing roundabouts. The most well-known fully empirical roundabout capacity model is the LR942 linear regression model. It used a statistical multivariate regression analysis to fit mathematical relationships between the circulating flows (Q_C) and the measured entry flow (Q_e) (Yap, Gibson, & Waterson, 2013). Multivariate regression is a statistical technique that determines the relationship between one dependent variable and multiple independent variables. It can show if changes in the dependent variable could be associated with changes in the independent variables. This is done by comparing the dispersion of the data around a best-fit line.

In the case of the linear regression model (LR942), the independent variables are the geometric elements; e the entry width (m), φ angle (°), and r the radius (m); v the approach half width (m); L the effective flare length (m); and D the inscribed circle diameter (m). These parameters are used in the equations created by Kimber (1980).

$$Q_E = max\{K[F - f_c q_c],0\} \quad \textit{Eq. 1}$$

Where K, F, and f_c, are determined by the following equations.

$$K = 1 - 0.00347(\phi - 30) - 0.978(1/r - 0.05) \quad \textit{Eq. 2}$$

$$F = 303x_2 \quad \textit{Eq. 3}$$

$$f_c = 0.210t_D(1 + 0.2x_2) \quad \textit{Eq. 4}$$

$$t_D = 1 + \frac{0.5}{1+exp\frac{D-60}{10}} \quad \textit{Eq. 5}$$

$$x_2 = v + \frac{e-v}{1+2s} \quad \textit{Eq. 6}$$

$$s = \frac{1.6(e-v)}{L} \quad \textit{Eq. 7}$$

The limitations of this model are however, that it is not fully understood theoretically how individual independent variables influence the dependent variable. It should also be noted that this model only works on specific situations. It must be adapted to situations that do not fully overlap with the situations this model has been calibrated for. In the case of LR942, pedestrians and cyclist crossings have not been taken into consideration.

4.3.2. Gap Acceptance Modelling

Another approach for modelling the capacity of a roundabout is gap acceptance modelling. It is based on parameters from measurements of individual headways between circulating and entering vehicles used to create theoretical models (Yap, Gibson, & Waterson, 2013). It relies on three variables to determine entry capacity; The critical gap (t_c), Follow-on headway (t_f); Poisson distributed arrivals.

Eq. 8 is a gap acceptance model based on negative exponential headways. It also includes critical gap, follow-on headway and circulating traffic (Q_c) parameters. This is a more simplified model derived by Siegloch from Tanner's model. The differences in the models are that Siegloch assumed a non-clustered Poisson distribution of the arrivals and used a continuous, rather than a discrete function, for the long gaps (Fortuijn, 2009).

$$Q_e = \frac{3600}{t_f} e^{-Q_c(t_c-(t_f/2))} \quad \textit{Eq. 8}$$

There are lots of different gap acceptance models with their own assumptions, variables, and distributions. However, as can be seen in Figure 5, when calculating the capacity with the same arrival distribution are negligible, but the differences increase at high opposing flow rates between various gap acceptance models. The opposing flow rate of a roundabout is the circulating flow rate (Q_c).

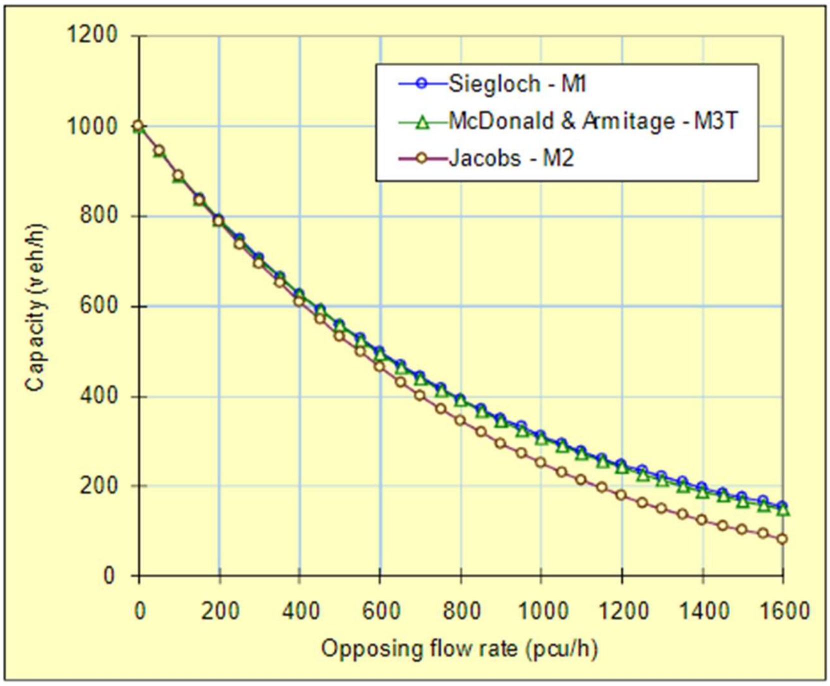


Figure 5: Capacity and Opposing flow rate for the same gap acceptance. (Akçelik, 2007)

4.4. Microsimulation Models

Microsimulation traffic models are computer-based models that analyse individual persons and vehicles, and their interactions based on parameters a 'real' traffic network can be simulated and used to gather data. Vehicle movements are dependent on models within the simulation model and all their movements are calculated for every individual vehicle at every time-step. To represent real human-driver behaviour, driving behaviour parameters are stochastically assigned to every individual vehicle using Monte Carlo methods with specified probability distributions to introduce 'real world' variability (Yap, Gibson, & Waterson, 2013).

4.4.1. VISSIM

VISSIM is a microsimulation model software package that can perform multi-modal traffic flow simulation developed by PTV. It allows the user to model any traffic situation, as well as their geometrics. VISSIM also contains powerful analysis tools and options to create tools that use VISSIM data as input to optimize the data gathering. The modelling process consists of using functions to create a traffic network, and changing parameters such that it fits the traffic scenario. Driving behaviour parameters are assigned stochastically to a specified vehicle.

VISSIM allows almost every aspect of the traffic network to be altered, however for this research project most of the parameters can be kept at their default values, since these default parameters have already been extensively researched by the developer PTV Planung Transport Verkehr AG in Karlsruhe, Germany. The main focus will be on the systems that specify the driving behaviour of the vehicles. While road specifications will be modelled according to CROW and Goudappel standards, and traffic rules will be modelled after the Dutch traffic laws, the behavioural patterns also need to be adapted to the Netherlands. This difference mostly lies in gap time and gap distance, due to The Netherlands being a bit more comfortable driving on roundabouts. AVs will also have to be modelled using the driving behaviour parameters, gap distance, and gap time.

VISSIM is based on two car following models, Wiedemann 74 and the updated version Wiedemann 99. The Wiedemann model takes into account the psychological aspects and physiological restrictions of the perception of a driver, this is called the psycho-physical car-following model (PTV VISSIM, 2024). Wiedemann designed his car following model based on the assumption that there are four different driving states, see Figure 6 where d is distance and Δv is the speed difference.

The four driving states are; Free driving [1], where there is no influence from other cars and the driver seeks to maintain oscillating around his desired speed; Approaching [3], the driver approaches a car ahead and starts adapting his speed, such that when the safety distance is reached there is no difference in speed; Following [2], the car proceeds to follow the car ahead by unconsciously adapting his speed, such that the speed difference oscillates around zero; Braking [4], whenever the desired safety distance threshold has been surpassed the car starts to decelerate.

Wiedemann 74, as mentioned before, has been updated in 1999 and additional parameters have been added that can be used to calibrate car following behaviour. They are still based on previously mentioned four different driving states, but the parameter count went from three to ten, see Appendix A – Wiedemann 99 Parameters.

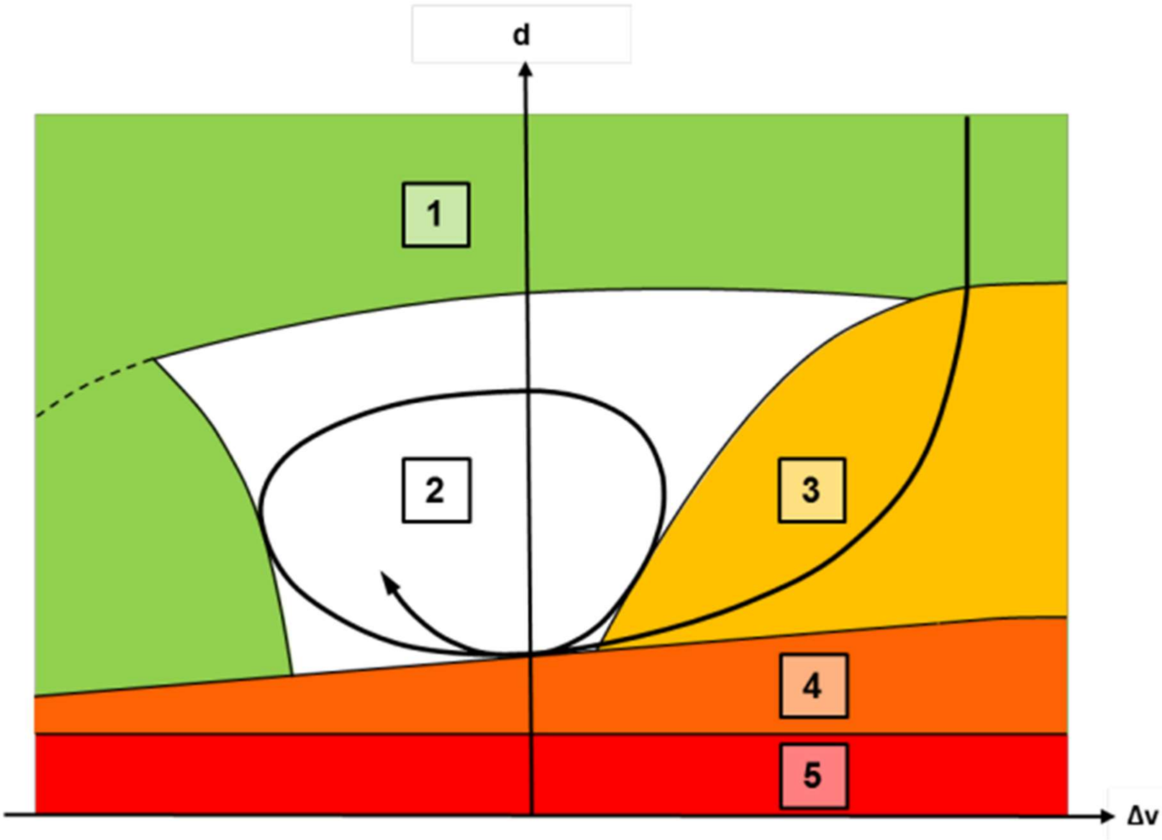


Figure 6: Car following model Wiedemann 74 (PTV VISSIM, 2024).

5. Methodology

In this chapter the methodology will be explained. It follows the steps in the flowchart, see Figure 7. This flowchart consists of three parts, modelling, simulation, and analysis.

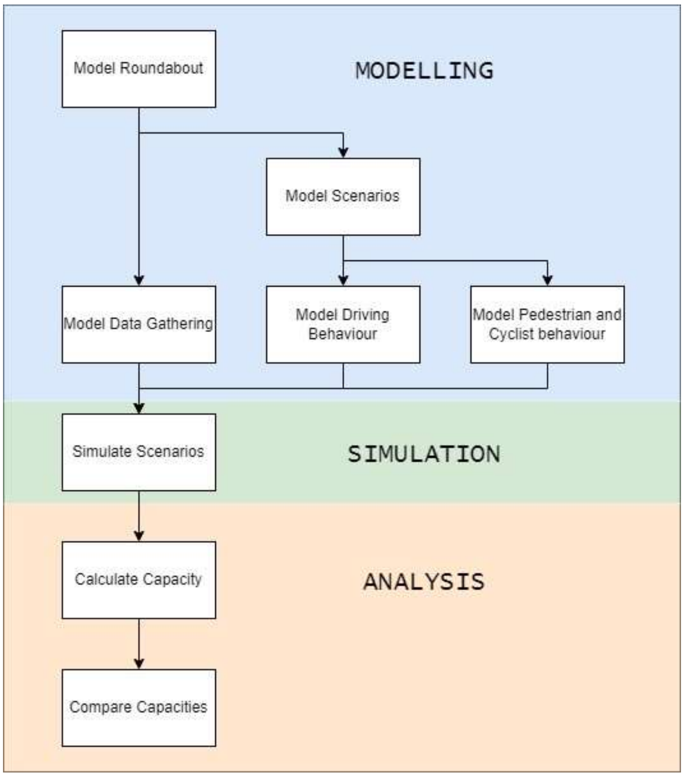


Figure 7: Flowchart Methodology

5.1. Modelling

The flowchart starts with making the base model of the roundabout. This will be done using the traffic microsimulation software VISSIM. It will be modelled according to the recommendations from CROW and Goudappel. The base model will contain splitter islands, which already are of appropriate length to facilitate cyclist and pedestrian crossings. There will be four legs modelled that attach to the roundabout with the correct alignment, as was mentioned in Chapter 2.2.2., they will be radially aligned.

When the base model is modelled correctly, cyclist and pedestrians can be added to create new scenarios, such that the four final scenarios will be base, cyclist, pedestrian, and both. As the names imply, the base scenario only considers vehicle traffic, while the other three will include cyclists, pedestrians and both respectively. This allows the analysation of the impact of these two roundabout facilities and AVs on the capacity the roundabout.

Both the pedestrian and the cyclist behaviour will have to be modelled, as well as the AV behaviour. The AV behaviour will be modelled using the Wiedeman 99 model in VISSIM. The Wiedeman 99 model uses 10 parameters, which if used correctly can reflect the driving behaviour of a real-world driver or AV. However, due to this model only considering SAE level 4 and 5 vehicles and these not existing in the current traffic ecosystem, their behavioural parameters are quite uncertain. Therefore, multiple AV types will be modelled. These AV types depend on their behaviour. This leads to three AV types, cautious, normal, and aggressive. These three AV types will use parameters from literature.

There are 4 different parts that will influence the number of scenarios that will be simulated, see Table 4. As discussed in the previous parts, user types and AV types are two of these, the other two are the AV penetration rate and the major flow scenarios. The AV penetration rate will go from 0% to 100% in increments of 20%. The major flow scenarios consist of three scenarios. The first and second scenarios depend on what flow will become the major flow, this is either the entrance flow or the circulating flow. Where the circulating flow is the same as the entrance flow is the third scenario. The total amount of scenarios is therefore 192.

Table 4: Scenario Sheet

Scenario Sheet

User Type

#	NV	AV	HGV	AHGV	PED	CYC
1	YES	YES	YES	YES	NO	NO
2	YES	YES	YES	YES	YES	NO
3	YES	YES	YES	YES	NO	YES
4	YES	YES	YES	YES	YES	YES

AV Penetration rate

#	AV PR (%)
1	0
2	20
3	40
4	60
5	80
6	100

AV Type

#	Type
1	Cautious
2	Normal
3	Aggress.

Major Flow

#	Flow
1	Entrance
2	Same
3	Circulating

Base *Included* *Excluded*

Total # Scenarios 192

5.2. Simulation

The model will be used to simulate a large number of scenarios that depend on the changes in the model regarding user types, major flow scenarios, AV penetration rates and AV types. The amount of runs necessary to get to a certain confidence level is hard to determine due to the stochasticity of VISSIM. If the behaviour parameters have been changed, which will be the case for most of the scenarios that will need to be simulated, it will be even more complex to determine a fitting number of runs. Because of how complex it is, many agencies require a minimum number of runs for the results to be acceptable. These range from 5 to 20 runs, where most agencies require at least 10 (Fries, Qi, & Leight, 2017). This requirement also holds at Goudappel, so the standard of 10 runs from Goudappel be used for every scenario. However, in order to find the maximum capacity, 50 runs were used per scenario. This decision was made to have more points for a smoother capacity curve.

5.3. Analysis

To properly analyse the impact of AVs on the entrance capacity of a roundabout, first the capacity of the base model will be determined. This base capacity can be used for the starting point of further simulation runs. The other simulation runs with 0% AV penetration rates are considered the base scenarios. In Table 4, this has also been marked with a shade of blue.

When the maximum capacity of the base scenario has been determined, the maximum capacity of the scenario with the most optimal conditions will be simulated, which is assumed to be when the AV penetration rate is 100%. This allows for optimized simulation times, since the range of the capacity has been found. The model will start from the base scenario capacity and the traffic flow will increase in small increments over time. It will also have a warmup and cooldown period.

To find the effects of the pedestrian and cyclist crossings, the intensity of the pedestrian and cyclists flows will not increase over time. They will stay constant and only give a quick insight into the capacity drop when these crossings are active compared to the base scenario with no facilities.

The main outputs that will be analysed are the output and difference in input and output. The output over time should increase and once the capacity has been reached, the output should stabilize. The difference in flows should fluctuate around a starting point, if the time increments at which the flow is measured is not too small, this starting point should be close or equal to 0. If this is not the case and the starting point is higher, it is due to cars still being within the gap between the measurement points of the inflow and outflow. The other two inputs that will be analysed are queue delay and length. These are not very representative of the maximum capacity, as they can fluctuate a lot and the point at which the maximum capacity has been reached, is unclear. This is the due to the queue length and delay going up slowly, once the maximum capacity has been reached. It will increase faster afterwards, but together with the fluctuations, it is difficult to pinpoint the exact maximum capacity.

6. Model Setup

This chapter contains information regarding the base model. This will include the layout, design elements, network objects, and data gathering in Vissim.

6.1. Layout and Design Elements

The layout and design elements are based on standards from Goudappel and CROW. The model is used by Goudappel for quick and standardized intersection calculations. This model fits within the CROW standards and will be used and altered to find the impacts of AVs in different scenarios, the final model can be seen in Figure 8.

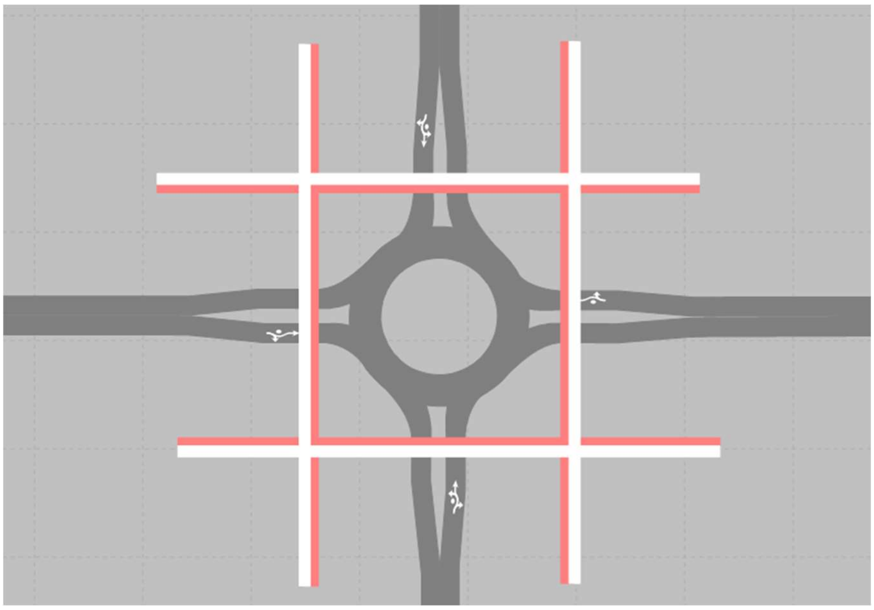


Figure 8: Layout Model

The model is setup with four similar legs connecting to a roundabout with an inner (Rbi) and outer (Rbu) radius of respectively 10.70m and 16.50m, meaning that the circulating lane width (B) is 5.80m. The entry curve radius (Rt) is 12.00m and the exit curve (Ra) is 15.00m. The entry (Bt) and exit (Ba) lane width are both 3.50m. The layout also uses splitter islands, the splitter island width (Bm) is 3.00m and the splitter island length (Lm) is 15.00m. The splitter islands will facilitate pedestrian and cyclist crossings, where pedestrians can cross in both directions and cyclists only in the driving direction. Together the pedestrian and cyclist crossing width (Bpc) is 5.00m, while the distance from the circulating traffic to the crossing (Lpc) is 4.00m. This will allow one car to roughly fit in between if the vehicle cannot directly enter the circulating traffic. The geometric parameters of the design elements have been summarized in Table 5.

In real scenarios the overrun area, which is included in the inner radius (Rbi), is important for HGVs. However, it is not possible to implement this in Vissim. The actual impacts of the overrun area and the overrun slope will not be considered as this is outside of the scope of this research project just as the impacts of other geometric changes in design elements.

Table 5: Design Elements Model

Design Element	Standard (m)
Outer radius (Rbu)	16.50
Inner radius (Rbi)	10.70
Circulating lane width (B)	5.80
Overrun area	*
Entry curve radius (Rt)	12.00
Exit curve radius (Ra)	15.00
Entry lane width (Bt)	3.50
Exit lane width (Ba)	3.50
Splitter island width (Bm)	3.00
Splitter island length (Lm)	15.00
Ped. and Cyc. path width (Bpc)	3.50
Ped. and Cyc. path distance (Lpc)	5.50
***Overrun Area not in Vissim**	

6.2. Network Objects

Network objects are the building blocks of Vissim. They allow users to build a network and make it reflect the real world. This chapter discusses the network objects used for both the traffic network and data gathering. The visualization of the discussed network objects can be found in Appendix B – Model Setup.

6.2.1. Traffic Network

The traffic network uses links to act as the roads, pedestrian paths and bicycle paths. These links can be assigned vehicle types through link behaviour. Link behaviour will be discussed in further detail in Chapter 7.1. The desired speed is used to roughly 50 meters before the entrance to the circulating flow, to lower the speed to 25 km/h. Roughly 5m after the exit of the circulating flow, the desired speed has been set to 50 km/h. A reduced speed area has been implemented at every entrance of the circulating flow and the speeds differ, for cars the reduced speed area has been set to 25 km/h and for HGVs to 15 km/h. The reason it has been setup this way is due to how these network objects interact with vehicles in the network. Desired speed lets the vehicles know that they have to change to the desired speed once they have passed the desired speed ‘sign’. With the 50m between this sign and the entrance, it will reflect reality where a car starts decelerating when getting close to the roundabout. The reduced speed area is there to force vehicles to change their speed in that area, this means that their speed will be reduced to the set reduced speed and will keep driving until the speed will be changed again either with reduced speed areas, or desired speed signals.

There are two ways to model priority in Vissim, conflict areas and priority rules. Conflict areas are very easy to use, as they show conflict areas due to overlapping or connecting links. However, this does not allow for very detailed simulation work regarding the roundabouts and different types of vehicle driving behaviours. At roundabouts, the circulating traffic has priority. This is also the case for the pedestrians and cyclists. However, the vehicles that do not have priority can enter the priority road based on gaps between priority traffic. There are two types of gaps, distance and time gaps. If there is quite a bit of distance between the entering vehicle and the vehicle on the priority road, the vehicle can enter, this is the gap distance. This differs for every vehicle type, due to acceleration and vehicle length. If a car is driving relatively slow compared to other vehicles on the priority road, the entering vehicle can decide to enter even if the gap distance is smaller. This is because the vehicle knows that the time necessary for the vehicle to enter is shorter than what the vehicle on the priority road needs, to get to that point. This is called the gap time, and it depends on acceleration and the speed of vehicles on the road that it is trying to enter. Four priority rule areas have been setup for each leg. The first and second priority rule are used to give pedestrians and cyclists crossings priority from vehicles that enter and exit the roundabout. The third priority rule is for circulating traffic, the entering leg has to give priority. The fourth priority rule is setup on the circulating road for the entering leg. This is not used to give priority to entering vehicles, but as a safety measure. If a vehicle decides to enter the circulating road but due to congestion the vehicle has to slow down or even come to a halt on the entering section circulating traffic can seize priority and drive over this entering vehicle due to how Vissim works. This priority rule is therefore used to reflect reality as this situation would not occur in a real situation. When a car is entering, the circulating traffic would not drive over this vehicle. Actual gap times and gap distances will be discussed in Chapter 7.1.

Traffic flow can be simulated using either static vehicle routes or dynamic assignment. A static vehicle route means that the route of a vehicle will not change no matter the circumstances, in complex situations this is not realistic. If certain part of the route is too congested or not accessible at all, it will try and follow a different route this is what dynamic assignment is used for. However, this traffic network is relatively simple in nature, due to only having a single intersection which consists of a single lane roundabout with pedestrian and cyclist facilities. Static routes will be used for pedestrians and cyclists, as they will only cross the road once and disappear from the traffic network. For vehicles dynamic assignment will be used to allow detailed matrices and other simulation options to be implemented. Dynamic assignment requires parking lots that function as origin and destination points for nodes, vehicles can then decide the optimal route from their origin to their predetermined destination. However, as mentioned before this function is mainly necessary for the usage of OD matrices and other functions.

6.2.2. Data Gathering

There are four main ways to collect data in Vissim. Nodes can be used to evaluate an entire intersection. However, it will sum all the results and is not able to provide information for each individual leg. Data collection points, vehicle travel times, and queue counters can be placed at entry and exit lane. This research requires queue delay, vehicle input and output of the entry legs, and queue length. The queue delay, vehicle input and output, will be measured using data collection points. The vehicle output of an entry leg will be called the entry flow. The entry flow will be measured at the entry point to the roundabout where it will intersect with the circulating flow. The vehicle input will be measured at a 1km distance from the entry flow measuring point. The vehicle input and entry flow will provide the difference in input and output and acts as the main way of finding the entry capacity of the roundabout. An additional 4 data collection points will be used to measure the circulating flow for every conflict point between the circulating flow and entry flow. The queue length is collected with queue counters, these measure the queue starting from the point where the queue counter is located. Queue counters are located at every entry point. Vehicle travel times will not be measured. A total of 12 data collection points and 4 queue counters have been placed.

Although the research is mainly about finding the entry capacity of one leg in different scenarios, every leg will be monitored. There are 4 big conflict points, one at each leg. These conflict points are the main cause of the entry capacity. While the OD matrix will be constructed in such a way that the traffic flow is the highest through the conflict point of interest, due to the stochasticity of the model every conflict point will be monitored to make sure the entry capacity found, is caused by the conflict point of interest.

7. Model Scenarios

This chapter contains all the information about the different 'building blocks' for the 192 different scenarios. The scenarios are based on different vehicle types, penetration rates, traffic intensities and the presence or absence of pedestrians and cyclists.

7.1. Vehicle Types

To model the AV penetration rates and other things the vehicle types need to be modelled in Vissim first. The vehicle types are based on two different behaviours, following behaviour also known as the Wiedemann 99 model and the exit and entry of the roundabout behaviour which is modelled in Vissim using priority rules. The vehicle types are implemented in Vissim by creating vehicle compositions and adding vehicle types with relative flows. Relative flows determine how much of the flow rate (veh/h) is going to be that specific vehicle type.

A total of 8 vehicle type have been modelled, in short these are conventional vehicles, cautious, normal and aggressive AVs. These 4 also contain corresponding HGVs that have the same behaviour parameters but have a larger size. While some research projects have different parameters for smaller and heavier vehicles Goudappel has recently started using the same parameters for both. As it would lead to some problems during simulations and would not represent reality. The main difference is the gap time of 0.2s higher than for a heavy vehicle compared to a smaller vehicle. Which would cause these larger vehicles to sometimes not enter the roundabout in full capacity conditions at all. In real scenarios a truck would force their way onto the roundabout after having to wait for too long, and with the removal of the 0.2s difference in gap time, the issue was fixed as it reflected real data much better.

7.1.1. Priority Rules

The priority rules are setup in Vissim, such that there is a gap time and a minimum clearance, see Table 6. The gap time is the leading factor in determining the capacity and therefore changes in this parameter will influence the capacity of the roundabout the most. The minimum clearance is used as a safety measure to ensure that during the simulation, vehicles do not collide or drive on top of each other when the roundabout is in a congested state. Both the pedestrian and cyclist crossing have the same gap time and clearance. The priority rules for entering the roundabout, however, are slightly different. Goudappel calibrated their Vissim model parameters based on empirical data and deduced that Dutch drivers drive more aggressively compared to the default parameters of Vissim, which is based on German research. The default parameter is set on a gap time of 3.0s, equalling the gap time used for cautious AVs. But for a Dutch roundabout 3.0s is too slow and was lowered to 2.8s, which is used for normal AVs. In Table 6 the roundabout entry has an additional parameter, which is the 'MaxSpeed'. This parameter is linked to the minimum clearance of the roundabout entry. As mentioned before the minimum clearance is a safety measure, but during a free flow state on the roundabout a minimum clearance is not necessary. Since it can be assumed that vehicles do not collide if the speed is higher than noted in Table 6. The 'MaxSpeed' parameter means that the minimum clearance is only working when the speed of the vehicles is lower than specified. The current settings are assumptions based on brief speed and distance calculations and another assumption that cautious vehicles will always use the minimum clearance rule as they behave according to their name. The 5.0m is based on the geometrical aspects of the roundabout, such that the road is clear and when congested there is enough space between the car on the circulating lane and the entry lane.

Table 6: Priority Rules Chosen Parameters.

Priority Rules

Type	**Car & HGV**	**Car & HGV AV**		
Behaviour	Normal	Cautious	Normal	Aggressive
Pedestrian Crossing				
Min. Gap Time (s)	3.0	3	2.8	2.6
Min. Clearance (m)	2.3	2.3	2.3	2.3
Cyclist Crossing				
Min. Gap Time (s)	3.0	3	2.8	2.6
Min. Clearance (m)	2.3	2.3	2.3	2.3
Roundabout Entry				
Min. Gap Time (s)	2.8	3	2.8	2.6
Min. Clearance (m)	5.0	5.0	5.0	5.0
*MaxSpeed (km/h)	20	180	20	16

*When the speed is higher than the max the priority rule is not used.

7.1.2. Wiedemann 99 Values

The Wiedemann 99 model parameters were directly obtained from a recent study project called CoEXist related to the implementation of AVs in Vissim with Rupprecht Consult as coordinators (Rupprecht Consult GmbH, 2020). Together with PTV Vissim an example was created that could be loaded in Vissim containing cautious, normal and aggressive behaving AVs. Table 7 shows the Wiedemann 99 parameter values for both normal and autonomous vehicles. AVs differ mostly in their values from manual driven cars, because they lack human input. They can act more precise and react quicker, meaning that some of the car following parameters can be set close to or at zero.

Two parameters are set to zero, CC2 and CC6. CC2 is the following variation, AVs will be able to strive for almost no variation in its following behaviour as it can immediately react to how the vehicle in front is behaving, due to being computer driven. The reasoning behind CC6, speed dependency on oscillation being set to zero, is the same. The speed dependency of oscillation will stay at zero due to being able to keep their speed very accurately (Bruijl, 2019).

The parameters CC4, CC5, and CC7 are the same for all AVs but differ from the manual vehicles. The negative and positive following thresholds CC4 and CC5 respectively are lower compared to manual vehicles as they can more accurately measure the speed of the leading vehicles and thus stay within the thresholds of following much more accurately. This is also connected to CC7 the acceleration and deceleration during the following process, where the AVs can control their speed accurately.

CC0, CC1, CC3, CC8 and CC9 are dependent on the aggressiveness of the vehicles. Some of the values for normal AVs are the same as manual vehicles, since as their type name implies, they behave almost the same as normal manual vehicles. Cautious vehicles are expected mainly during the early stages of the introduction of AVs into the traffic landscape and will be more cautious than manual vehicles to make sure to reduce accidents as much as possible. The reasoning behind their lower values is as discussed with previous parameters due to lack of human involvement and reliance on sensors and quick computation. Making the autonomous vehicles quicker and more accurate in reacting on their environment. Appendix A – Wiedemann 99 Parameters, shows the description of all the parameters.

Table 7: Wiedemann 99 Values.

Wiedemann 99				
Type	**Car & HGV**	**Car & HGV AV**		
Behaviour	Normal	Cautious	Normal	Aggressive
CC0 (m)	1.5	1.5	1.5	1.0
CC1 (s)	0.9	1.5	0.9	0.6
CC2 (m)	4.0	0.0	0.0	0.0
CC3 (s)	-8.0	-10.0	-8.0	-6.0
CC4 (m/s)	-0.4	-0.1	-0.1	-0.1
CC5 (m/s)	0.4	0.1	0.1	0.1
CC6 (1/(m*s)	11.4	0.0	0.0	0.0
CC7 (m/s^2)	0.3	0.1	0.1	0.1
CC8 (m/s^2)	3.5	3.0	3.5	4.0
CC9 (m/s^2)	1.5	1.2	1.5	2.0
Source	Goudappel	CoEXist		

7.1.3. Speed and Visibility

The speed of the different vehicle types, changes per road section. In the Vissim model there are three road sections, the main links (the four legs attached to the roundabout), the desired speed on the circulating link (the circular road of the roundabout), and the entry area (the transition road from the main link to the circulating link). While the manual and autonomous cars have the same speed for every road section the HGVs both manual and autonomous are slightly slower. For the main links the speed limit is set at 50km/h, while the roundabout is set at 25km/h. HGVs drive the same speed on the main links but are slower on the roundabout with 15km/h, see Table 8. The main limiter of speed at roundabouts is due to information processing, drivers need to take in a lot of information while on a roundabout in order to enter and exit. While AVs might be able to process information faster and react accordingly, the speed should not increase on roundabouts. This is because of the comfort of people in the AVs and also for pedestrians and cyclists that take part in the roundabout intersection.

Visibility or it can also be called the intake of data is important. The different vehicle types of some slight differences in the number of observed objects and vehicles, while Goudappel assumes that a manual driven vehicles interacts with most vehicles it can see within the observed distances both ahead and backwards. The AVs, however, are mainly interacting with the cars in front of them. Aggressive AVs are assumed to be more developed and can thus interact with more vehicles to also allow it to safely act more aggressive than its other AV counterparts. Table 9 contains the values used for the different parameters.

Table 8: Speed of each vehicle type on the different road sections.

Speed				
Type	**Car**	**HGV**	**Car AV**	**HGV AV**
Behaviour	Normal	Normal	All	All
MainLink (km/h)	50	50	50	50
DesiredSpeed (km/h)	25	15	25	15
ReducedSpeedArea (km/h)	25	15	25	15

Table 9: Visibility parameters of each vehicle type.

Visibility				
Type	**Car & HGV**	**Car & HGV AV**		
Behaviour	Normal	Cautious	Normal	Aggressive
Min. Ahead (m)	0	0	0	0
Max. Ahead (m)	250	250	250	300
NumInteractObj	5	2	2	10
NumInteractVeh	99	1	1	8
Min. Backwards (m)	0	0	0	0
Max. Backwards (m)	150	150	150	150

7.2. AV Penetration Rates

In the model the transition period consists of AV types with different penetration rates. Using increments of 20% starting from 0% till 100% the transition period can be modelled. Increments of 20% are chosen since most penetration predictions are based on the same increment. This has been mentioned in Chapter 4.1.3. An actual prediction of penetration levels will not be researched further in this assignment, only the AV penetration rates are of importance in this research. These increments will provide some insight into how different AV penetration rates will influence the capacity of the roundabout. Boualam et al. also used increments of 20% for AV penetration rates, but instead of researching the AV types cautious, normal, and aggressive. They combined them and used cautious at a penetration rate of 20%, normal for 40% and 60%, and aggressive for 80% and 100%. However, in this research project, the AV behaviours will be researched separately and thus each AV penetration rate will range from 0% to 100%. This has been applied in Vissim using scenarios where the relative flows of the different vehicle types have been adjusted accordingly to the 20% AV penetration rate increments.

7.3. Traffic Intensity

Three additional scenarios consist of differences in traffic flow ratios. This ratio is the circulating and entry flow. The opposing flow is the circulating flow that conflicts with its corresponding entry flow. The main entry flow that will be monitored is the entry from the west. U-Turns are not taken into consideration as these are very small traffic flows, unless there are some very specific conditions. Such as a road connecting to an entry leg that only allows right-hand turns, meaning that in order to turn left, traffic has to make a U-turn on the roundabout. Figure 9 shows the conflict point of the circulating traffic and the entry traffic with its traffic flows based on direction. Using Figure 9 an OD matrix can be created that shows the entry, opposing (conflicting circulating flow with the entry flow) and rest flows of the west-leg, see Table 10.

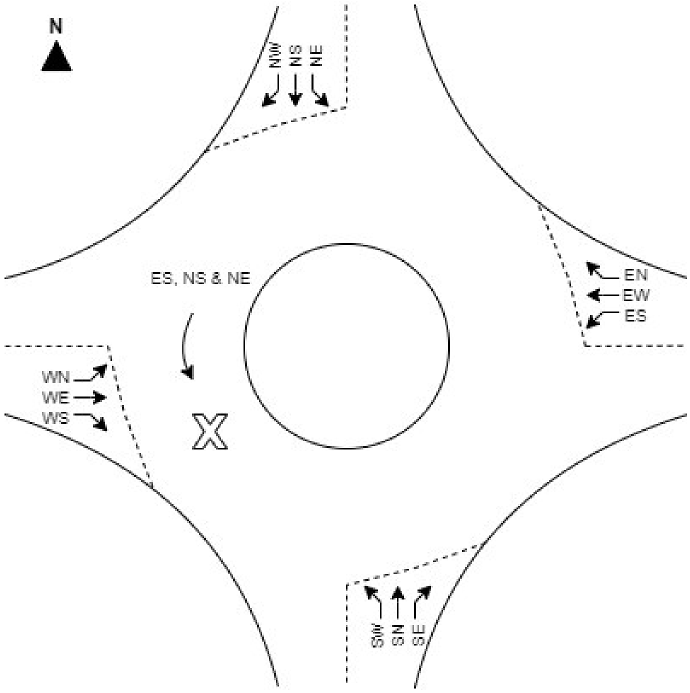


Figure 9: West-Entry Leg, Conflicting Traffic Flows.

Table 10: OD Matrices Traffic Flow Relations indicating entry, opposing and rest flow rates.

OD Matrix East-leg

O\D	East	South	West	North
East		Entry	Entry	Entry
South	Rest		Opp.	Opp.
West	Rest	Rest		Opp.
North	Rest	Rest	Rest	

OD Matrix South-leg

O\D	East	South	West	North
East		Rest	Rest	Rest
South	Entry		Entry	Entry
West	Opp.	Rest		Opp.
North	Opp.	Rest	Rest	

OD Matrix West-leg

O\D	East	South	West	North
East		Opp.	Rest	Rest
South	Rest		Rest	Rest
West	Entry	Entry		Entry
North	Opp.	Opp.	Rest	

OD Matrix North-leg

O\D	East	South	West	North
East		Opp.	Opp.	Rest
South	Rest		Opp.	Rest
West	Rest	Rest		Rest
North	Entry	Entry	Entry	

Following the previous OD matrices a relative flow OD matrix is made as basis. The opposing and entry flows will be increased using increments of a number of vehicles, while the rest stays the same amount. Three intensity scenarios have been created based on entry/opposing ratio, 25/75, 50/50 and 75/25. The rest will be calculated as 10% of the initial vehicle volume. Meaning that the first ratio will consist of 67.5% opposing volume, 22.5% entry volume, and 10% rest volume. The rest volume will stay the same through testing to act as a small volume that makes sure the situation stays representative as some events only happen with vehicles on all legs. Such as the 'scheinconflict' this takes depends on the blinking behaviour of a vehicle on the circulating road and influences when a vehicle from the entry flow can start entering. These smaller effects are not part of the research and instead will be kept constant throughout the research process. The relative flow OD matrix for both intensity scenarios are shown in Table 11.

Table 11: Relative Flow OD Matrices for Different Entry/Circulation Flow Ratios.

OD Matrix 25/75 Ratio

O\D	East	South	West	North	SUM
East		0.225	0.017	0.017	0.258
South	0.017		0.017	0.017	0.050
West	0.075	0.075		0.075	0.225
North	0.225	0.225	0.017		0.467
SUM	0.317	0.525	0.050	0.108	1.000

OD Matrix 50/50 Ratio

O\D	East	South	West	North	SUM
East		0.150	0.017	0.017	0.183
South	0.017		0.017	0.017	0.050
West	0.150	0.150		0.150	0.450
North	0.150	0.150	0.017		0.317
SUM	0.317	0.450	0.050	0.183	1.000

OD Matrix 75/25 Ratio

O\D	East	South	West	North	SUM
East		0.075	0.017	0.017	0.108
South	0.017		0.017	0.017	0.050
West	0.225	0.225		0.225	0.675
North	0.075	0.075	0.017		0.167
SUM	0.317	0.375	0.050	0.258	1.000

7.4. Cyclists and Pedestrians

Cyclists and pedestrians are taken into account to see the impact on the capacity of a roundabout entry leg, while also seeing the effects of how different AV types interact with pedestrians and cyclists. This is done by modelling in a constant flow of just pedestrians, cyclists or both. These scenarios can then be compared to the scenario without these flows. The parameters of the cyclists and pedestrians are kept the same as used by Goudappel. Pedestrians will cross the roads at a flow of 100 pedestrians per hour. Since they can cross both ways, a flow of 50 pedestrians per hour is used for each cross direction adding up to 100 pedestrians per hour per leg. Cyclists also have a flow of 100 cyclists per hour per entry leg but can only cross in the driving direction. This flow is also kept constant and does not vary. Cyclists are also kept at Goudappel standards, just like the pedestrians. This is to make sure that the results can be compared to not only the base scenario modelled but also models from Goudappel.

The flows itself are kept constant and do not fluctuate to ensure that every scenario is tested with the same conditions regarding pedestrians and cyclists. While it would also be beneficial to look into how different flow rates of pedestrians and cyclists would interact with different AV types, this would create to many scenarios and data process and report within the time constraints for this bachelor’s thesis of 10 weeks.

8. Simulation Setup and Data Processing

The model has been setup such that the simulation time is 75 minutes. During this period there is a warmup time for vehicles to enter the system, as well as a cooldown period. Both are 10 minutes of simulation time. The warmup matrix is the same OD matrix as the starting matrix of the data collection. The data collection interval starts at the end of the warmup period and ends at the start of the cooldown period. The measurements intervals are 5 minutes, resulting in 12 measurements. The increase in the opposing and entry flow also takes place every 5 minutes. The 12 OD matrices can be found in Appendix C.1. – OD-Matrices.

The Vissim model uses a random seed with random seed increments of 1. Meaning that every run will be different, as Vissim assigns values to vehicles stochastically based. Random seeds assures that no previous runs will be the same. In Chapter 5.2 it was already discussed that 50 runs per scenario were going to be used. This is due to the large number of scenarios and differences in parameters. In most organisations 10 runs per scenario would be enough validation for the result. However, 50 runs were chosen for this research to make sure that it is reliable.

A multi-run tool was used from Goudappel to make the running process less labour intensive as without it, making sure that the data is organised and easy to access. The output of the multi-run tool was used to import it in Excel. Since the raw data included every single leg, the data was filtered down to just vehicle counts of the west entry and opposing flows. The other data regarding queue length and input flows into the system were used to verify the model.

The maximum value of the vehicle counts of every run were taken and used to create a cumulative distribution function (CDF) for every single scenario. It was assumed that every scenario had a normalised distribution. See Appendix C.2. – Normality Test for the results and a more detailed explanation of the normality test. The final capacity values were taken at the 0.5 probability value mark, which is the mean of the maximum of the vehicle counts. This CDF gives an insight into how the capacity is expected to be influenced by its scenarios. A value lower than 0.5 has a probability of being a value less than or equal to the 0.5 probability capacity.

With the large number of scenarios, it is important to know how to the naming system works, to read the graphs. A name (example: 1_20_AV_C_PB) starts with a number from 1 to 3, which shows the flow ratio scenarios from 25/75, 50/50, and 75/25 respectively. It is then followed up by the penetration rate from 0 to 100 in steps of 20. The vehicle type is either CV for the conventional vehicles or AV_C (Cautious), AV_N (Normal), and AV_A (Aggressive) for the autonomous vehicles. The ending indicates if there are pedestrians and or cyclists present with P (pedestrians), B (Bikes) and PB for both. A summary of the naming system is located in Appendix D.1. – Naming System.

9. Results

This chapter contains all the results from the Vissim model. Due to the large number of scenarios, not every graph will be explained in detail. This also means that not every graph will be in this chapter, all the CDF graphs can be found in Appendix D – Entry Capacity CDF. The capacity values can be found in Appendix F – Capacity, showing the values itself as well as the change (in %) compared to its base scenario and colour coded with red being a decrease and blue an increase.

The system is in a state of free flow when the input and the output of a single leg is the same. When the output is lower than the input, the system starts to form congestions. In Figure 10, the output and input flows of the West leg for ratio 25/75 run 1 can be seen. It shows how the output reaches the max at 29 vehicles at time 3000s, and afterwards the max is not reached again and is now fully congested. The input-output progression also reinforces this, as in Figure 11 the difference is shown. This graph is expected to stay around 0 as the vehicles the same number of vehicles should be outputted as inputted when the entry leg has not reached capacity. When the maximum is reached of 29 vehicles at 3000s, the Output-Input graph shows that the entry leg has reached capacity, since the difference starts to increase drastically. The ratio over time has also been monitored and as it is simulated stochastically, the ratio will not stay the same as intended over time, see Figure 12. It is also not a clear indication of when a capacity is reached, the ratio of 25/75 holds for the entirety of the simulation while already having reached capacity. However, the observed runs of 50/50 and 75/25 show a clear negative trend when the capacity has been reached. The graphs regarding the observations for all three scenarios can be found in Appendix E – Observations Run 1.

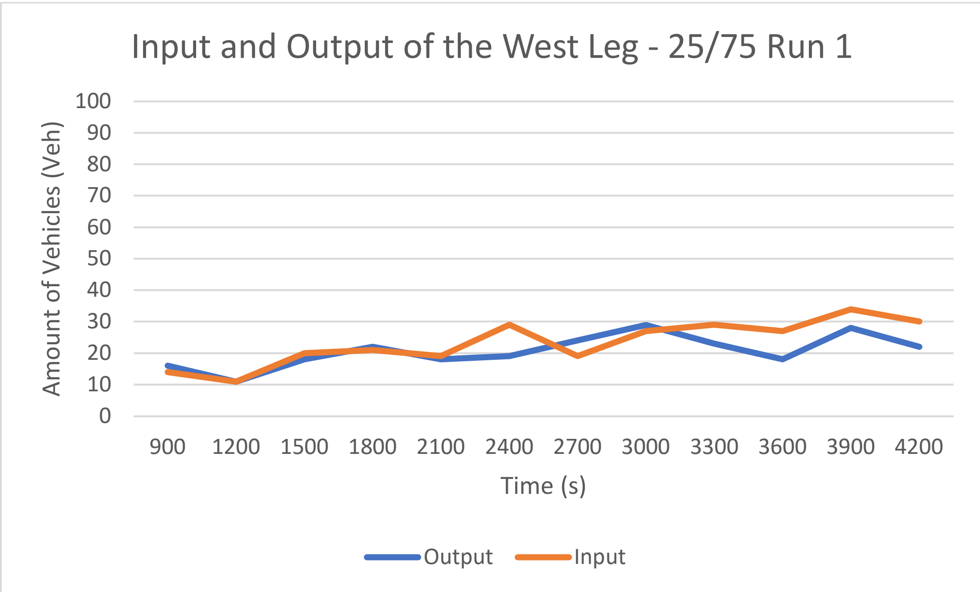


Figure 10: Input and Output of the West Leg - 25/75 Run 1.

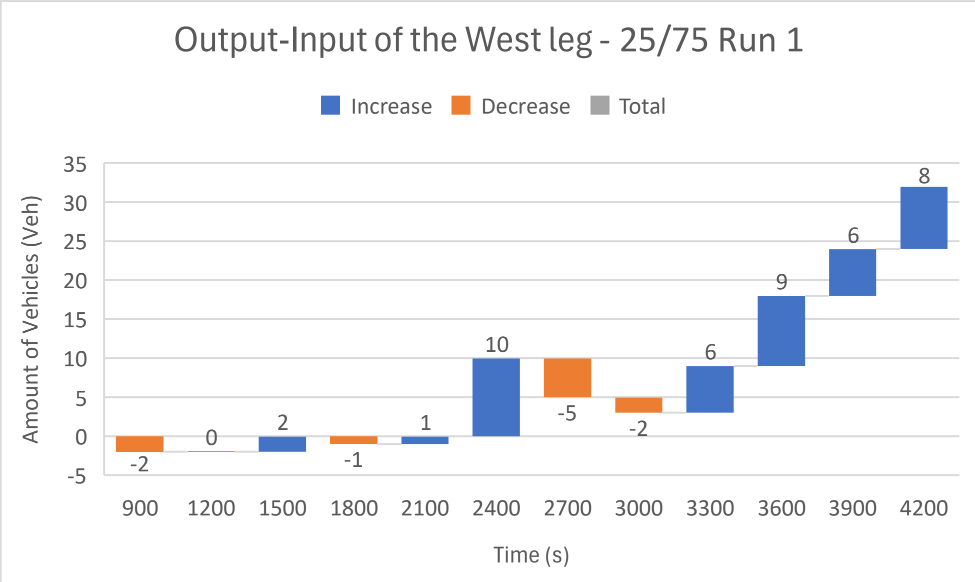


Figure 11: Output-Input of the West leg - 25/75 Run 1

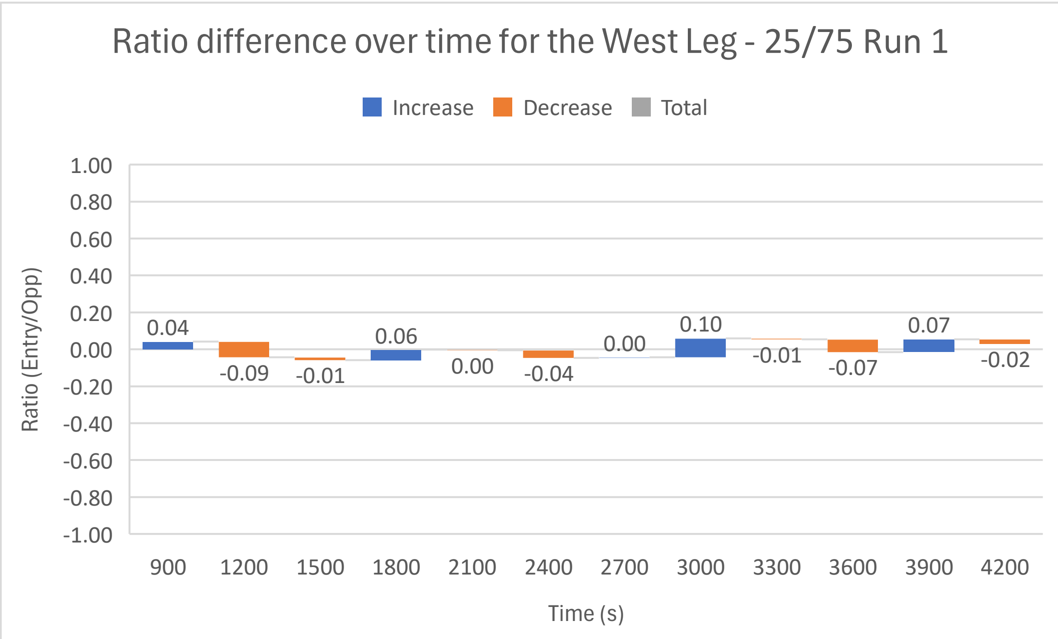


Figure 12: Ratio difference over time for the West leg - 25/75 Run 1

The base scenarios for the traffic scenario 25/75 are close to each other in capacity, see Figure 13. There is a slight decrease in capacity compared to the base scenario due to the presence of cyclists and pedestrians. This is as expected due to pedestrians being slower compared to bikes, meaning that the vehicles can start accelerating earlier when they come to a halt.

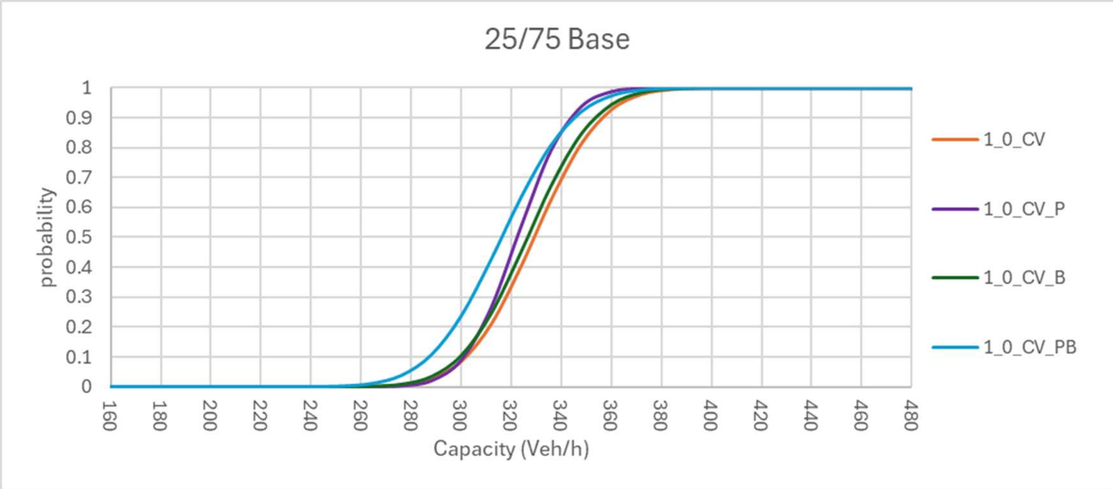


Figure 13: CDF 25/75 Scenario.

9.1. Vehicle Types

In Figure 14 the CDF graphs for the 25/75 entry/opposing ratio for every vehicle type are shown. For both aggressive and cautious AVs there is a large difference compared to the base scenario, while the normal AVs are much closer to the CVs. Due to the parameters in Vissim for both CVs and normal AVs being very close and thus behaving nearly the same. The normal AV scenarios for every ratio are very close to the base scenario. Cautious AVs have a lower capacity and each increase in penetration rate lowers the capacity further. Because cautious AVs are less aggressive than CVs, a decrease of CVs leads to a decrease in capacity. The opposite is true for aggressive AVs, the decrease in CVs leads to a higher capacity, as aggressive AVs are more aggressive when it comes to entering behaviour compared to CVs.

As for how the capacity increases and decreases, an increase in penetration rate for cautious AVs leads to a gradual decrease in capacity compared to the base scenario until 60% penetration. From there the capacity is still increasing but the rate of capacity increase gradually slows down. This happens for 25/75 scenarios, however for 50/50 the decrease in entry leg capacity is very linear. Which is also the case for 75/25, but for 50/50 it happens at a steeper angle. A linear decrease in entry capacity with increasing penetration rate is also observed for normal AVs. The rate at which it increases also grows with higher entry flow ratios. The same observation was made for cautious AVs when comparing 50/50 and 75/25 scenarios. Instead of a decreasing entry capacity, aggressive AVs cause an increase in capacity as mentioned before. Similarly to cautious AVs the rate of change in the entry capacity over high penetration rates decreases starting from 60% for the 25/75 scenarios. For 50/50 and 75/25 the entry capacity increases and similarly to cautious and normal AVs, the growth with increasing penetration rate is very linear. But for 50/50 the rate of growth in entry capacity is higher compared to 75/25. As can be seen in Table 12, the capacity for every 75/25 scenario changes very little compared to the other two ratio scenarios. It is difficult to pinpoint exactly what the reason is, since there are so many variables. But a possible explanation could be that the entry flow is so large that only the car following model parameters (Wiedemann 99 model) are determining the capacity in this ratio scenario. And these parameters do not have a lot of weight when doing so. Therefore, a threshold in entry/opposing ratio exists such that the car following parameters become more important than roundabout entry behaviour. And these car following parameters do not have as of a large impact on the entry capacity compared to the roundabout entry behaviour of vehicle types. Where this threshold lies is uncertain and needs to be researched further, however this is outside the scope of this research as it does not fit in the timeframe.

The largest capacity increase compared to their base scenario is 20.8% for Aggressive AVs at 100% penetration rate for scenario 25/75. The largest decrease is -22.8% for cautious AVs at 100% penetration rate for scenario 25/75 as well.

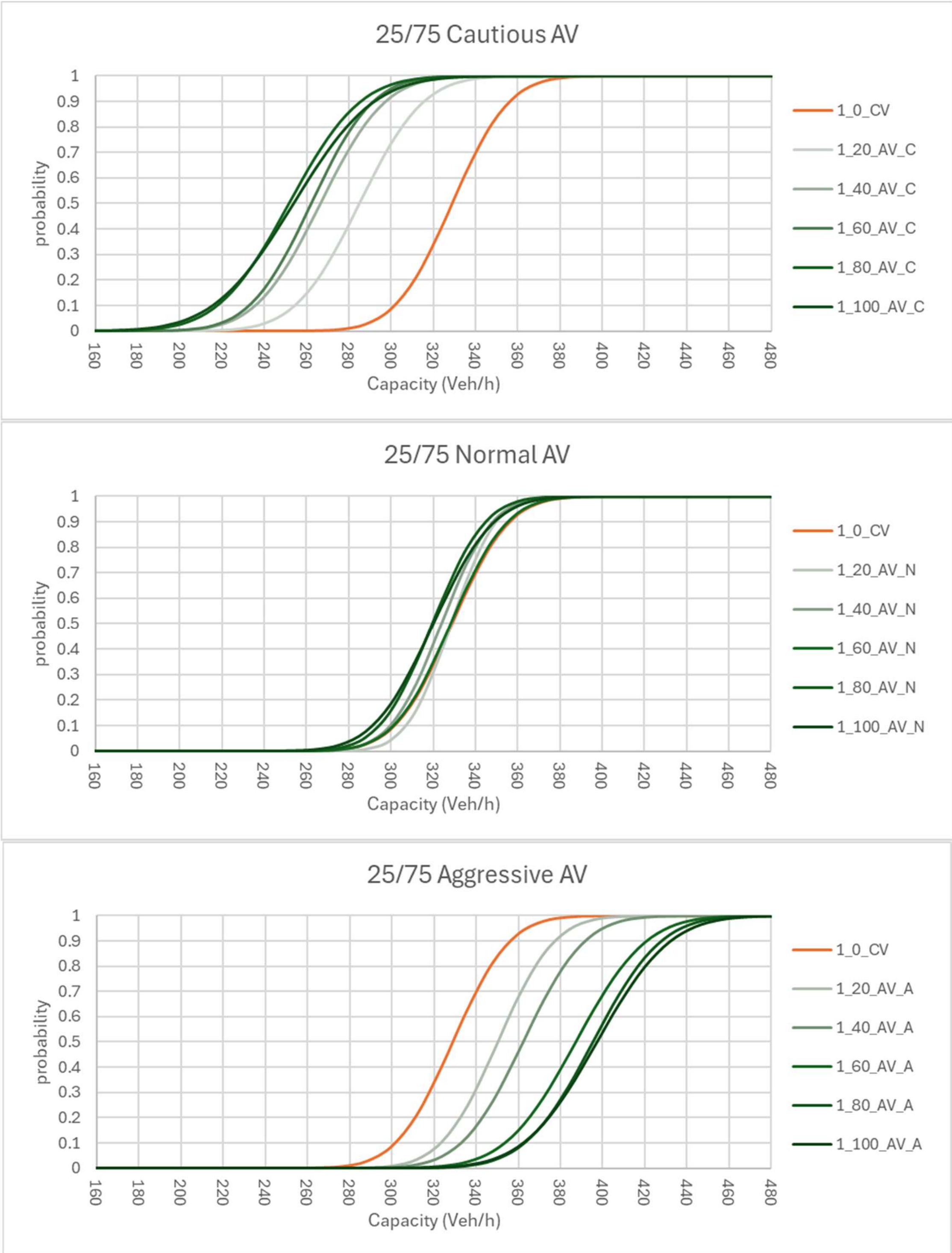


Figure 14: Entry capacity CDF Graphs of different Vehicle Types for Traffic Scenario 25/75.

Table 12: Entry capacity for every ratio and PR (%) scenario.

Entry capacity for every ratio and PR (%) scenario									
	25/75			**50/50**			**75/25**		
	Base Cap (Veh/h)		329	Base Cap (Veh/h)		566	Base Cap (Veh/h)		824
PR	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**
20%	285	329	350	536	552	570	803	813	823
40%	267	324	362	520	557	592	793	805	824
60%	262	328	387	507	549	613	772	795	829
80%	252	320	396	494	542	635	755	778	830
100%	254	320	397	481	538	669	735	769	833
Entry capacity change compared to their respective CV scenarios									
	25/75			**50/50**			**75/25**		
PR	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**
20%	-13.3%	-0.1%	6.5%	-5.4%	-2.5%	0.6%	-2.6%	-1.3%	-0.1%
40%	-19.0%	-1.5%	10.1%	-8.1%	-1.7%	4.5%	-3.7%	-2.3%	0.0%
60%	-20.3%	-0.2%	17.7%	-10.4%	-3.1%	8.2%	-6.3%	-3.6%	0.6%
80%	-23.5%	-2.8%	20.2%	-12.7%	-4.3%	12.1%	-8.4%	-5.6%	0.7%
100%	-22.8%	-2.7%	20.8%	-15.0%	-5.0%	18.1%	-10.8%	-6.7%	1.1%

9.2. Pedestrians

When pedestrians are involved, the capacity of an entry leg decreases. This was shown in the small CDF graph presented and discussed in the introduction of this chapter. The main observations regarding the trend of capacity growth also holds for pedestrians, it just has a lower base capacity compared to scenarios without pedestrians, as can be seen in Figure 15 and Table 13. There are two differences however, first the normal AVs for 25/75 start at an increased capacity compared to their base scenario till 40% normal AVs is reached. Meaning that a combination of 0% to 40% penetration rate of normal AVs with conventional vehicles is beneficial for the capacity of the roundabout with pedestrians. For 50/50 the starting point is already a decrease in capacity. Secondly the aggressive AVs for scenario 75/25 have a capacity just below the base scenario. This is mostly likely, because the starting point of 20% is not enough to make a noticeable difference in the capacity and due to the stochasticity of the model they are 0.09% off the base scenario. The highest increase in capacity is 22.0% for the 25/75 scenario with aggressive AVs and the highest decrease in capacity is 23.2%, which is also for the 25/75 scenario but with cautious vehicles.

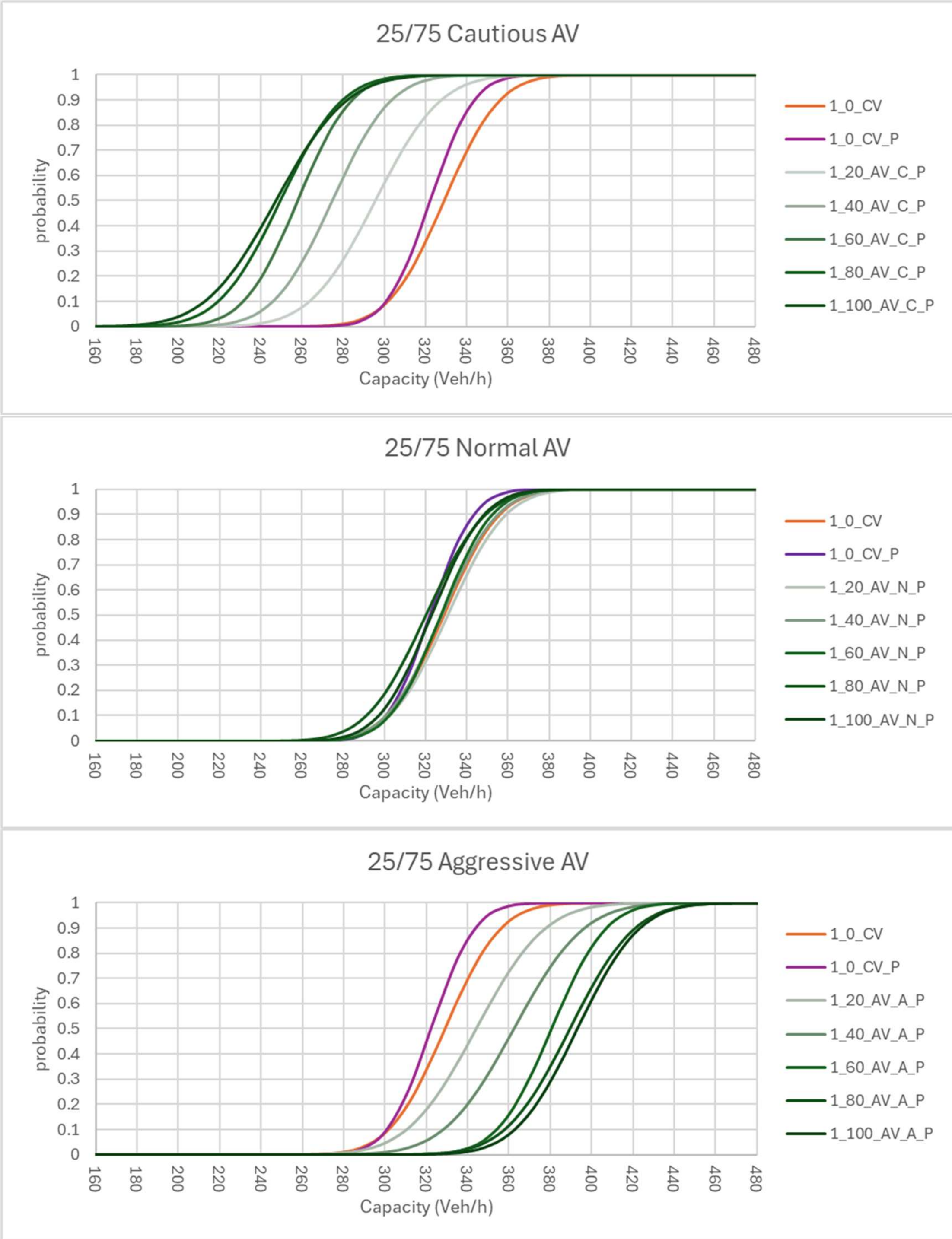


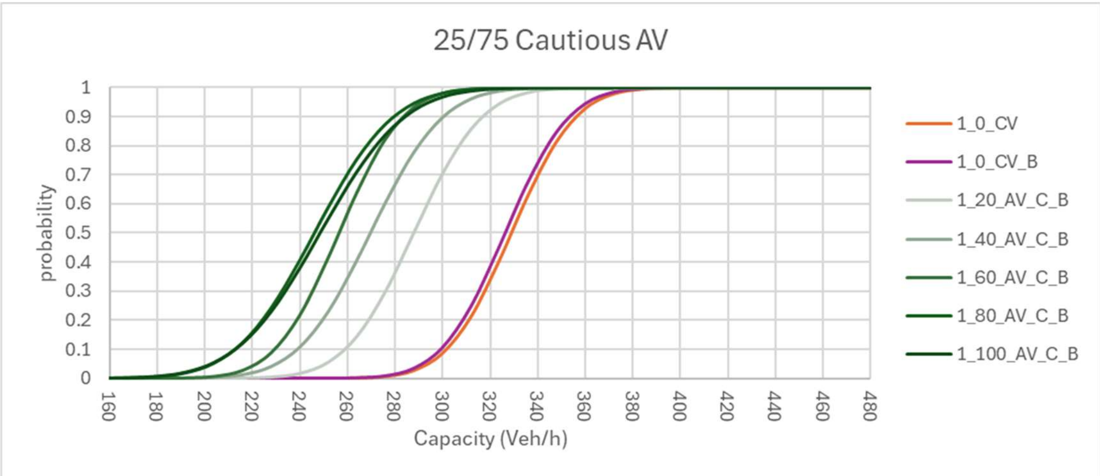
Figure 15: Entry capacity CDF Graphs of different Vehicle Types for Traffic Scenario 25/75 with pedestrians.

Table 13: Entry capacity for every ratio and PR (%) scenario with pedestrians.

Entry capacity for every ratio and PR (%) scenario with pedestrians									
	25/75			**50/50**			**75/25**		
	Base Cap (Veh/h)		322	Base Cap (Veh/h)		534	Base Cap (Veh/h)		767
PR	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**
20%	296	331	344	517	529	539	754	756	767
40%	275	328	362	505	526	559	741	755	775
60%	258	328	381	487	525	585	720	744	778
80%	250	320	390	469	522	598	709	733	777
100%	247	323	393	461	522	631	684	719	779
Capacity change compared to their respective CV scenarios									
	25/75			**50/50**			**75/25**		
PR	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**
20%	-8.3%	2.7%	6.8%	-3.1%	-0.9%	1.0%	-1.8%	-1.5%	-0.1%
40%	-14.7%	1.8%	12.4%	-5.3%	-1.4%	4.9%	-3.4%	-1.6%	1.0%
60%	-20.0%	1.6%	18.1%	-8.8%	-1.6%	9.7%	-6.1%	-3.1%	1.4%
80%	-22.6%	-0.6%	20.8%	-12.0%	-2.2%	12.0%	-7.5%	-4.5%	1.3%
100%	-23.2%	0.2%	22.0%	-13.6%	-2.2%	18.4%	-10.9%	-6.3%	1.5%

9.3. Cyclists

For cyclists the general results are the same as for pedestrians, however their initial capacity drop is a lower than pedestrians. Due to their faster speed, they cross the road faster and thus the road is less congested with bikes than pedestrians for the same volume per hour. The base capacity with bikes for aggressive AVs with 75/25 ratio is higher compared to the base scenario without pedestrians, due to aggressive AVs having a higher capacity in general. The highest increase in capacity can be observed for aggressive AVs at 20.5% and highest decrease -24.6% for cautious vehicles during the 25/75 scenarios, as can be seen in Figure 16 and Table 14.



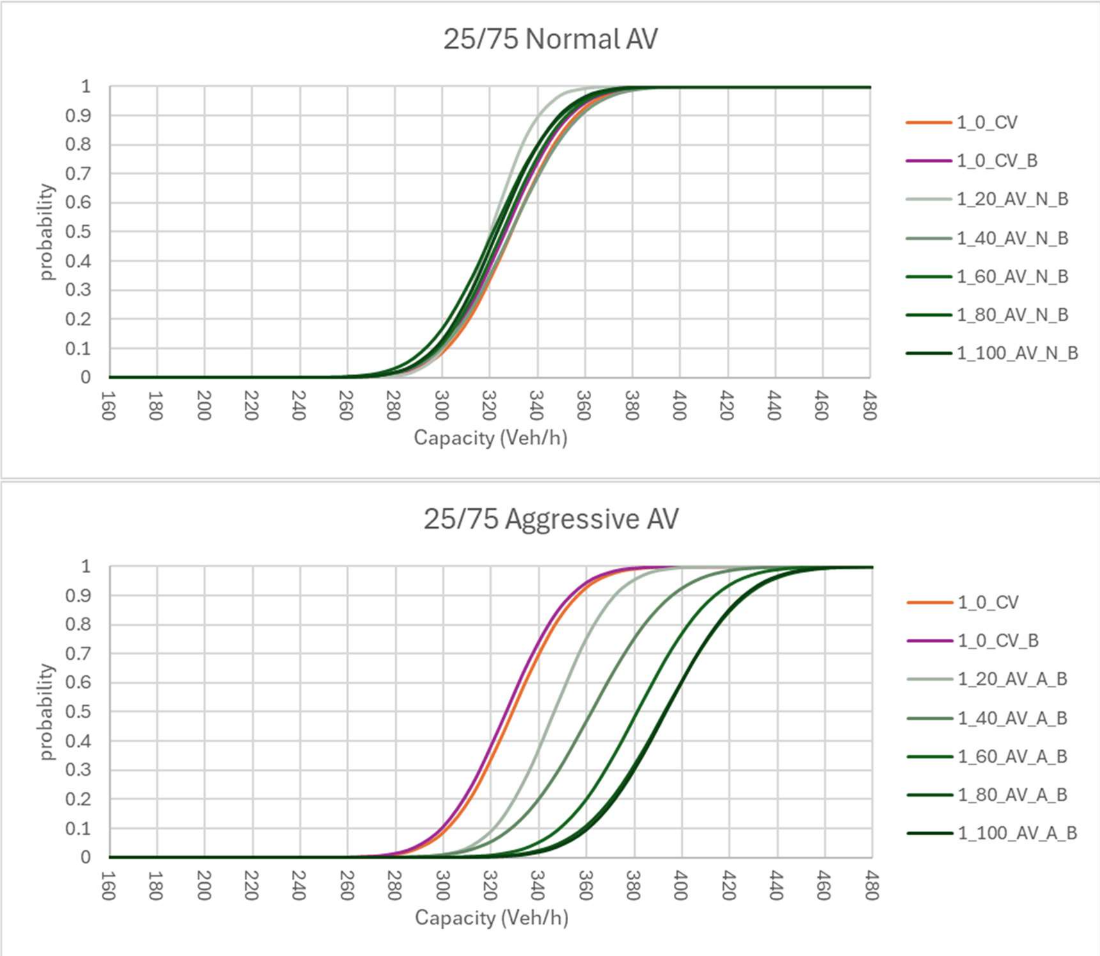


Figure 16: Entry capacity CDF Graphs of different Vehicle Types for Traffic Scenario 25/75 with cyclists.

Table 14: Entry capacity for every ratio and PR (%) scenario with cyclists.

Entry capacity for every ratio and PR (%) scenario with cyclists									
	25/75			50/50			75/25		
	Base Cap (Veh/h)		326	Base Cap (Veh/h)		542	Base Cap (Veh/h)		779
PR	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**
20%	288	320	347	521	531	546	758	768	784
40%	270	329	362	507	534	572	747	761	785
60%	257	325	381	489	528	588	734	753	784
80%	246	321	393	475	523	608	714	741	789
100%	249	323	393	474	524	641	698	733	794

Entry capacity change compared to their respective CV scenarios									
	25/75			50/50			75/25		
PR	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**	**Cautious**	**Normal**	**Aggres.**
20%	-11.8%	-1.8%	6.2%	-3.9%	-2.0%	0.8%	-2.7%	-1.3%	0.7%
40%	-17.4%	0.7%	11.0%	-6.5%	-1.5%	5.5%	-4.1%	-2.2%	0.8%
60%	-21.4%	-0.4%	16.8%	-9.9%	-2.7%	8.5%	-5.8%	-3.3%	0.6%
80%	-24.6%	-1.5%	20.4%	-12.4%	-3.6%	12.2%	-8.2%	-4.8%	1.3%
100%	-23.8%	-1.0%	20.5%	-12.7%	-3.4%	18.1%	-10.3%	-5.8%	2.0%

9.4. Pedestrians and Cyclists

When both pedestrian and cyclist flows are considered, the capacity drop is larger than just pedestrian or cyclist scenarios. But follows the same trend regarding change in capacity with the introduction of higher AV penetration rates, as can be seen in Figure 17. The largest decrease in capacity takes place during the 25/75 cautious AV scenario at 24.6%. While the largest increase can be observed in the same scenario but for aggressive AVs at 23.5%.

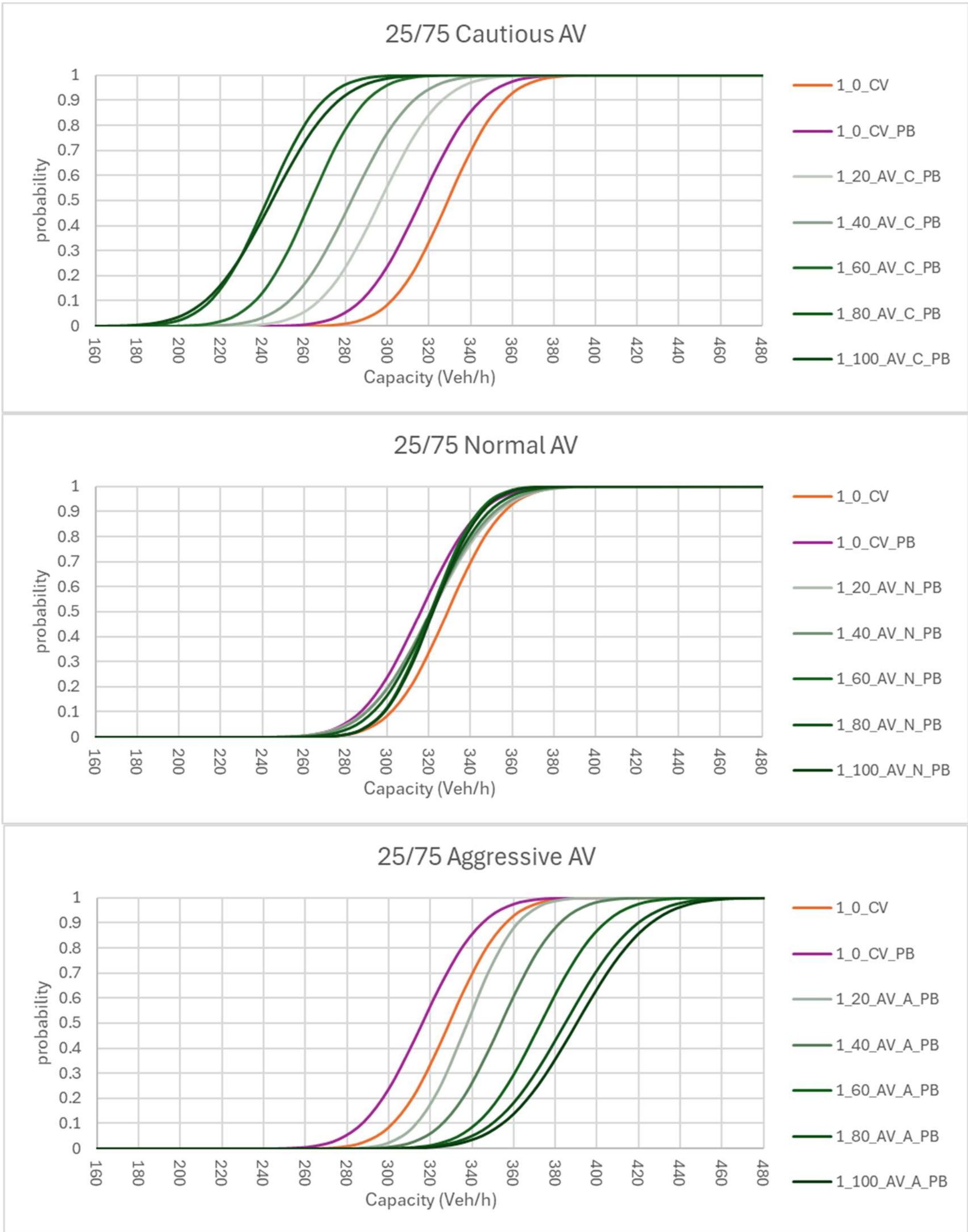


Figure 17: Entry capacity CDF Graphs of different Vehicle Types for Traffic Scenario 25/75 with pedestrians and cyclists.

Table 15: Entry capacity for every ratio and PR (%) scenario with pedestrians and cyclists.

Entry capacity for every ratio and PR (%) scenario with pedestrians and cyclists									
	25/75			50/50			75/25		
	Base Cap (Veh/h)		316	Base Cap (Veh/h)		511	Base Cap (Veh/h)		717
PR	Cautious	Normal	Aggres.	Cautious	Normal	Aggres.	Cautious	Normal	Aggres.
20%	297	321	338	493	511	521	706	710	725
40%	283	321	354	479	506	536	690	702	729
60%	263	321	373	470	503	560	682	700	738
80%	242	321	385	453	501	576	667	696	742
100%	245	322	390	451	503	605	652	687	743
capacity change compared to their respective CV scenarios									
	25/75			50/50			75/25		
PR	Cautious	Normal	Aggres.	Cautious	Normal	Aggres.	Cautious	Normal	Aggres.
20%	-6.2%	1.7%	6.8%	-3.5%	0.0%	1.8%	-1.51%	-0.90%	1.14%
40%	-10.6%	1.5%	12.0%	-6.3%	-0.9%	4.8%	-3.82%	-2.14%	1.71%
60%	-16.7%	1.6%	18.0%	-8.1%	-1.5%	9.6%	-4.85%	-2.31%	2.88%
80%	-23.4%	1.6%	21.7%	-11.5%	-2.0%	12.8%	-6.90%	-2.85%	3.55%
100%	-22.6%	1.9%	23.5%	-11.8%	-1.6%	18.4%	-9.01%	-4.15%	3.62%

9.5. Comparison

Conventional vehicles have a higher capacity than cautious AVs for every scenario regarding pedestrians, cyclists, and entry/opposing ratios. This can also be seen when plotting the entry capacity of each scenario against the opposing flow, which is based on the different ratio scenarios. This was done for every 100% penetration rate scenario, see Figure 18, Figure 19, Figure 20, and Figure 21. Normal AVs are very close to the CV scenarios and only for 75/25 scenarios do they have a relatively large impact on the entry capacity compared to lower ratio scenarios. While for cautious AVs this is the opposite, they have a smaller capacity drop at higher entry flows compared to opposing flows and the capacity drop increases over time. Aggressive AVs are also very close to CVs at higher entry flows, but instead of gradually increasing this gap with higher opposing flows, there is an optimal point. This optimal point is placed at roughly 600 opposing veh/h, the capacity difference is the highest there and although very slow this difference decreases with higher opposing flows. These trends are the same for every scenario, the only differences are the actual entry capacity numbers. Overall comparing the capacities to the respective base CV scenarios without pedestrians and cyclists over the three ratio scenarios, the largest increase in entry capacity is observed for 100% PR aggressive AVs for 25/75 with an increase of 20.8%. While the largest decrease has been found for 80% PR cautious AVs for 25/75 with pedestrians and cyclists. While it was to be expected that it was a scenario with cautious AVs, pedestrians and cyclists, the PR of 80% is surprising. While the 80% and 100% ratios are very close with 26.4% and 25.7% respectively, see Appendix F – Capacity. Due to the additional 20% CVs and the extra variation in parameters due to human driven cars. It most likely causes more problems for the entry traffic network and outweighs that of the more aggressive driving from CVs. Which would normally lead to an increase in capacity. Meaning that the 80% has a lower capacity than 100%.

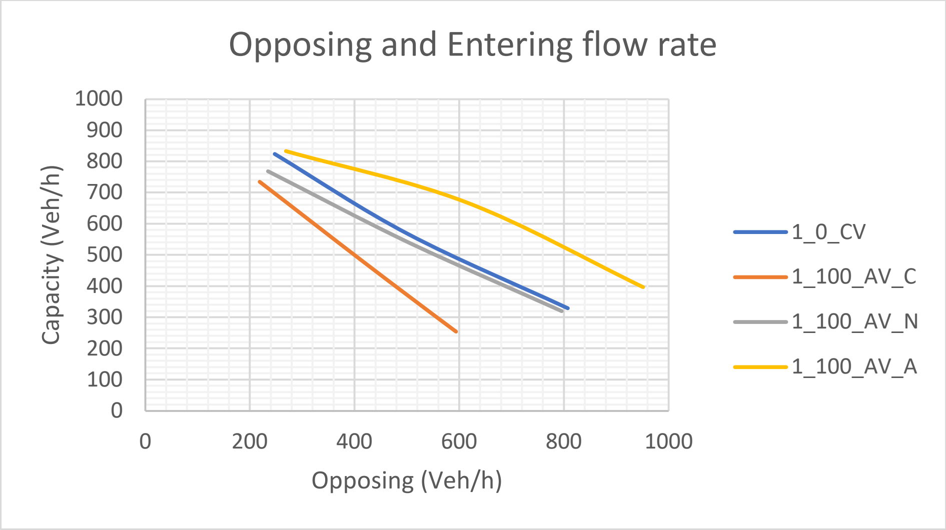


Figure 18: Opposing and entry flow rate of CV and 100% PR AV scenarios.

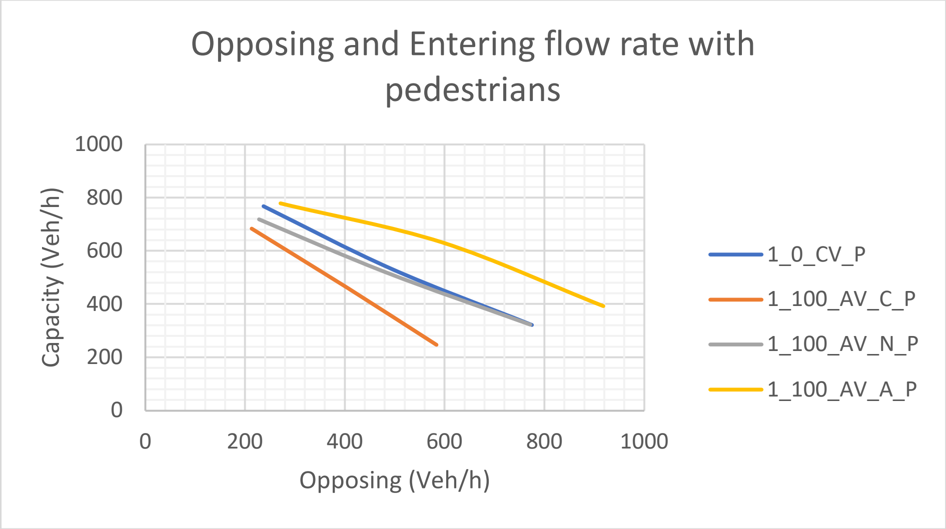


Figure 19: Opposing and entry flow rate of CV and 100% PR AV scenarios with pedestrians.

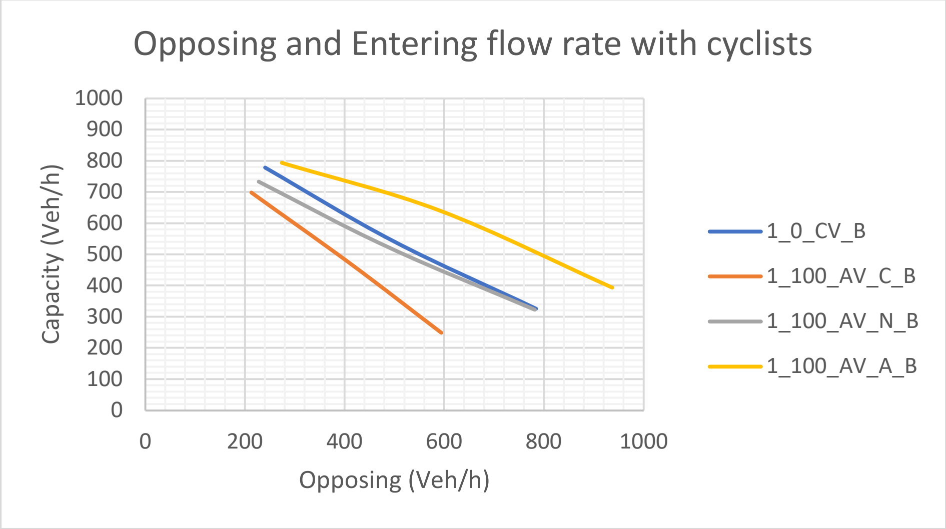


Figure 20: Opposing and entry flow rate of CV and 100% PR AV scenarios with cyclists.

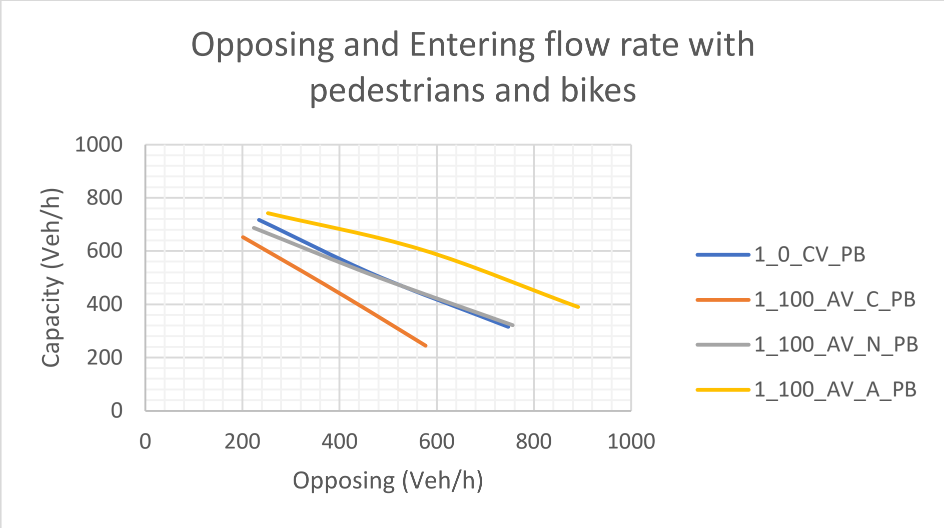


Figure 21: Opposing and entry flow rate of CV and 100% PR AV scenarios with pedestrians and cyclists.

10. Discussion and Recommendations for Future Research

Different topics and decisions will be discussed in this chapter and some recommendations regarding similar future research will be offered.

The model was as mentioned based on the ideal situation, where the roundabout had enough space to follow all the advised geometrical elements. However, these situations are rare in urban areas and compromises need to be made regarding these geometrical elements. Meaning that the current results are not applicable to those situations and the impact of these geometrical elements need to be further investigated.

AVs were modelled in Vissim using car following model Wiedemann 99 and other parameters for entering behaviour, visibility and speed limits. However, these parameters are mostly based on assumptions and AV projects as AVs do not currently exist in the current traffic landscape. Thus, the current results might not reflect the actual impact of AVs in the future. It only is gives us a small insight into how this road section (the roundabout) could be impacted.

It should also be noted that Vissim model had some parts that could have led to some inaccuracies. Such as the application of OD-matrices, they are stochastic, meaning that the model could decide at the start of the run, that a certain OD matrix will have its contents slightly altered. It was not possible to disable this stochasticity in Vissim. But instead of OD-matrices, vehicle inputs could have been used. These can be set as static and thus will not alter their content when a run starts. A further improvement of the OD-matrices could be made by using whole numbers. While Vissim can deal with decimals it will do so by adding one vehicle to run 1 and by not adding an additional vehicle when for example a ".5" is in the OD-matrix.

The OD-matrices were also all based on a situation where the opposing flow was distributed evenly over the legs that had traffic flows that caused conflicts with the observed entry leg. The other possible routes on the roundabout were called rest flows and their traffic flow stayed the same throughout the simulation. This was also the case for scenarios with pedestrians and bikes, these flows were kept at 100 bikes/pedestrians per hour. It was also assumed that the there were no vehicles making U-turns on the roundabouts, while this flow would be very minimal and very specific, the influence of such flow rates could give another insight into the workings of the roundabout.

For most topics discussed a sensitivity analysis would have been helpful. Possible sensitivity analysis's that would further improve the understanding of the results would be looking into different OD matrix constructions, changes in AV parameters (entry and car following parameters), pedestrian and cyclist volume per hour, and geometrical elements.

For this research the max was taken of each run to find the capacity of the roundabout, this method was decided upon after studying the first results. However, with the inaccuracies and stochasticity it is not clear if this is a good method. While the model was verified, and the results were validated by comparing results to other similar studies. With the number of scenarios not all of them were able to be manually checked.

More median/cumulative frequency graphs would have been a better indication of how capacity is influenced by all these different vehicle types and their penetration rates, as well as entry/opposing flow ratios. Assuming it was normally distributed, which was also not the case for every scenario, tails and medians would provide a better insight and more observations could have been made. A few scenarios were uniformly distributed but it should have been tested more.

More entry/opposing ratio scenarios are required to further improve the opposing and entering flow rate graphs. Currently only three ratio scenarios have been modelled, but more ratios are necessary for a better understanding of the results.

Overall, there are a few recommendations that can be made based on the topics discussed in this chapter. First, more research into AVs to further improve the values used for the parameters to model AVs into Vissim. New research will be done and published every year, and these should be considered to improve this study. Secondly, the sensitivity of important parameters should be analysed to substantiate the results. Furthermore, the results to the research questions can be improved by increasing the number of graphs and scenarios.

11. Conclusion

This chapter will discuss the answers to the main research question and its sub-questions.

1. *How can the driving behaviour of AVs translate over to Vissim?*

Autonomous driving is part of automated driving, which can be translated into 5 different levels of automation. Level 4 and level 5 can be called autonomous vehicles, as the vehicles that qualify as level 4 and 5 are more accurate in their driving behaviour. This is mostly due to the removal of direct human interference. This allows vehicles to fit into smaller time gaps, drive closer together and overall reduce chances of crashing. Vissim is a microsimulation program, which can be used to model different traffic scenarios. While there are currently other models based on empirical data, there is no data regarding AVs. Therefore, microsimulation can be used to model AVs into models of road sections based on assumed driving behaviour. Driving behaviour can be modelled in Vissim using car following model Wiedemann 99 and priority parameters (in this case roundabout entry behaviour). Since it is based on parameters of vehicles that are not currently present in the traffic network, three different types of AVs have been established based on how aggressive they behave in a traffic network. These three were identified as cautious, normal, and aggressive autonomous vehicles. As their name implies, cautious AVs drive more cautiously than CVs, normal AVs are comparable to CVs, and aggressive AVs are more aggressive than CVs. Leading to a wide range of possible AVs that can partake in the traffic network of the future. The specific parameters can be found in Chapter 7.1.

2. *How to gather data from a roundabout in Vissim to determine the capacity?*

Using various measurement options in Vissim as explained in Chapter 6.2.2, the necessary data was acquired. The main tool in Vissim used for data collection was 'Data collection points', at important points in the model. Such as the input flow, entry flow, and opposing flow for every roundabout entry leg. It was quickly determined that the total of capacity of the roundabout cannot be measured with so many different variables in play, due to modelling vehicles with parameters that are mostly based on assumptions as well as future traffic flows. Therefore, the research was mostly centred around roundabout entry leg capacity. Meaning that the term capacity took a different meaning for this research. And the previously mentioned data gathering points were used to determine this capacity.

Runs were observed and it was concluded that taking the maximum of the vehicle count taken at intervals of 5 minutes can be considered the maximum capacity of an entry leg. These observations are discussed in the introduction of Chapter 9 and the graphs of the first run for every ratio scenario can be found in Appendix E – Observations Run 1.

3. *What is the roundabout capacity with different AV types and AV penetration rate scenarios?*

Three different AV types have been modelled in Vissim, cautious, normal and aggressive AVs. They generally behave as their name implies. And it can be concluded that cautious AVs would cause a drop in capacity compared to conventional vehicles, with the largest decrease being 26.4% at 80% penetration rate in entry capacity. Normal vehicles generally act like CVs, but for roundabouts their parameters are slightly worse off and thus cause a very small decrease in capacity, compared to their base scenarios. Aggressive AVs cause the highest increase in capacity, which is an increase of 20.8% at 100% penetration rate. With different entry/opposing flow rate scenarios it was determined that Aggressive AVs have higher capacity differences when the opposing flow increases, this is also true for cautious AVs. However, normal AVs would slowly decrease their capacity difference with higher opposing flows. For the entry and opposing flows these have been further discussed in Chapter 9.5. The exact capacity results can be found in Appendix F – Capacity.

4. *What are the effects of pedestrian and cyclist crossings on the roundabout capacity?*

The pedestrian and cyclist crossings were modelled in Vissim according to the geometrical standards of Goudappel and CROW. Meaning that they were considered in the most safe and optimal way. The pedestrian and cyclist flows were also both set at 100 per hour and these were kept static throughout the model run time. This might not reflect real situations but does provide a good insight into how pedestrians and cyclists impact the capacity of a roundabout entry leg. Pedestrians and cyclists caused a decrease in capacity. How this decrease in capacity develops is discussed further in Chapter 9.2, 9.3 and 9.4. Generally, they follow the same change in capacity as their base scenarios without pedestrians and cyclists, but with a decrease in capacity for every traffic scenario, see Chapter 9.5.

Main research question: *What is the impact of different AV types and penetration rates on the entry leg capacity of a Dutch four-way entry single-lane roundabout?*

Using the answers for the previous sub-questions, the main research question can be answered. Generally, the impact depends on how aggressive the AVs will be in the future. When AVs are introduced and they are very cautious due to regulations, low penetration rates or for other reasons, the capacity might drop by roughly 20% for an entry leg. If there are pedestrians and cyclists involved this decrease in capacity might even reach to 26%. However, an increase in penetration rates and aggressiveness of the AVs will cause the capacity to significantly increase depending on the entry and opposing traffic flow ratio. At 25/75, an increase of about 21% at 100% penetration rate can be expected, this increase in capacity decreases over higher entry flows compared to opposing flows.

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Appendices

Appendix A – Wiedemann 99 Parameters

This appendix contains the Wiedemann 99 parameters used to implement car following behaviour in Vissim.

Table 16: Wiedemann 99 Parameters (PTV VISSIM, 2024).

Parameters	Unit	Description
CC0	m	**Standstill distance**: The desired standstill distance between two vehicles. No stochastic variation. You can define the behavior upstream of static obstacles via the attribute **Standstill distance in front of static obstacles** (see "Editing the driving behavior parameter Following behavior" on page 318).
CC1	s	**Gap time distribution**: Time distribution from which the gap time in seconds is drawn which a driver wants to maintain in addition to the standstill distance. At a speed v the desired safety distance is computed as: $dx_{safe} = CC0 + CC1 \cdot v$ At high volumes this distribution is the dominant factor for the capacity.
CC2	m	**'Following' distance oscillation**: Maximum additional distance beyond the desired safety distance accepted by a driver following another vehicle before intentionally moving closer. If this value is set to e.g. 10 m, the distance oscillates between: dx_{safe} *und* $dx_{safe} + 10\ m$ The default value is 4.0m which results in a quite stable following behavior.
CC3	s	**Threshold for entering 'BrakeBX'**: Time in seconds before reaching the maximum safety distance (assuming constant speed) to a leading slower vehicle at the beginning of the deceleration process (negative value).
CC4	m/s	**Negative speed difference**: Lower threshold for relative speed compared to slower leading vehicle during the following process (negative value). Lower absolute values result in adopting a speed more similar to the leading vehicle.
CC5	m/s	**Positive speed difference**: Relative speed limit compared to faster leading vehicle during the following process (positive value). Recommended value: Absolute value of **CC4** Negative values result in adopting a deceleration speed more similar to the leading vehicle.
CC6	1/(m • s)	**Distance impact on oscillation**: Impact of distance on limits of relative speed during following process: • Value 0: Distance has no impact on limits. • Larger values: Limits increase with increasing distance.
CC7	m/s^2	**Oscillation acceleration**: Acceleration oscillation during the following process.
CC8	m/s^2	**Acceleration from standstill**: Acceleration when starting from standstill. Is limited by the desired and maximum acceleration functions assigned to the vehicle type.
CC9	m/s^2	**Acceleration at 80 km/h**: Acceleration at 80 km/h is limited by the desired and maximum acceleration functions assigned to the vehicle type.

Appendix B – Model Setup

This appendix contains pictures of network objects used in Vissim to setup a model of a roundabout. During scenarios where pedestrians and cyclists had a flow rate of 0 per hour the pedestrian and bike lanes were removed as well as their respective priority rules.

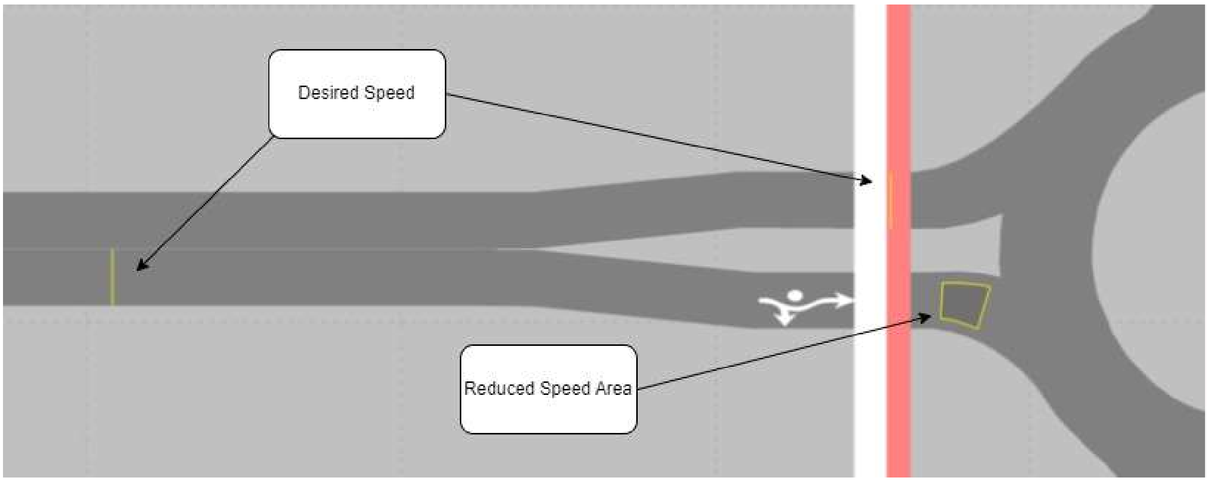


Figure 22: Desired and Reduced Speed Locations.

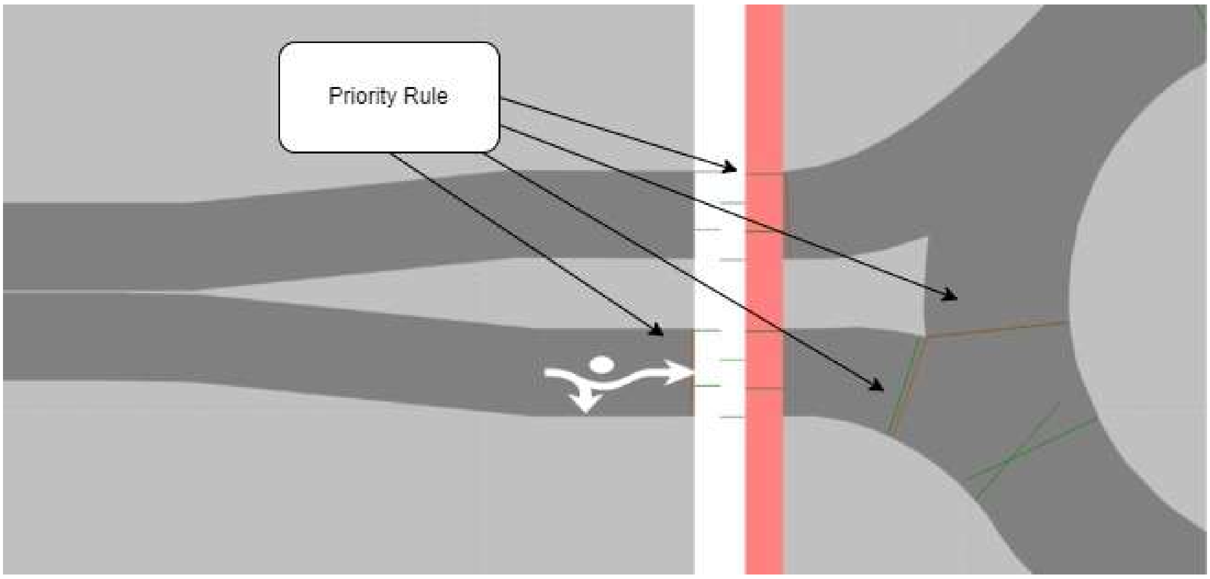


Figure 23: Priority Rule Locations.

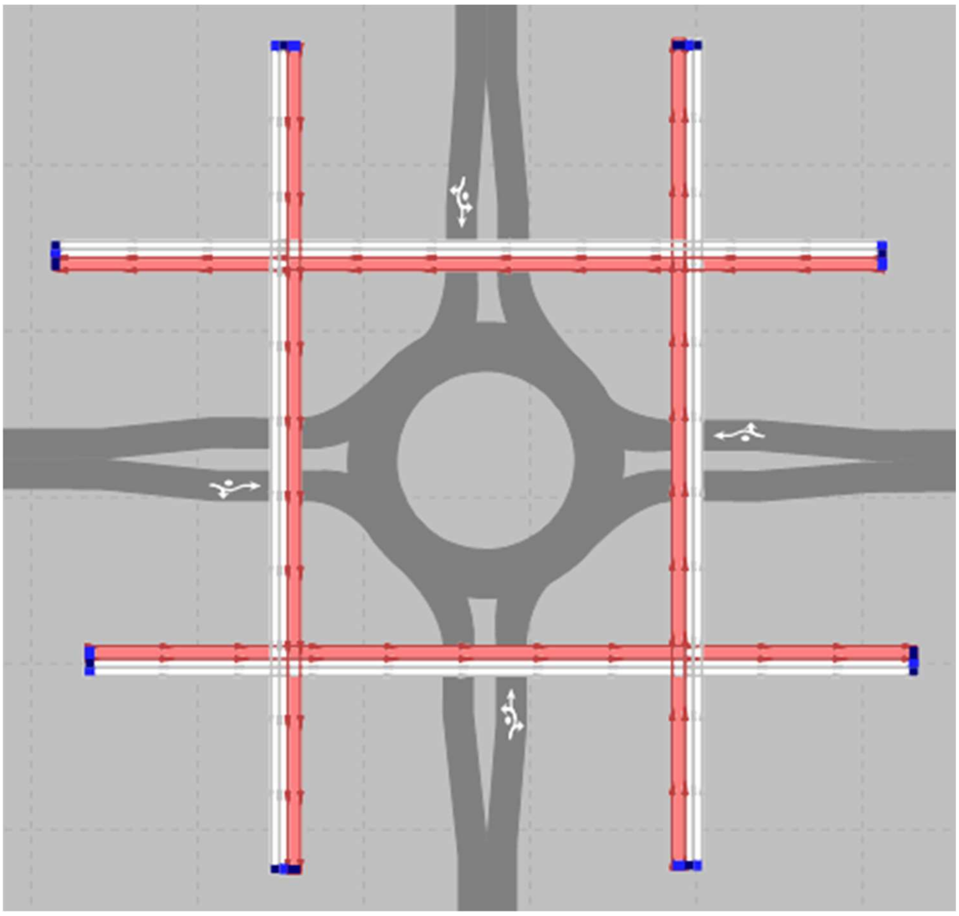


Figure 24: Highlighted Static Vehicle Routes for Pedestrians and Cyclists.

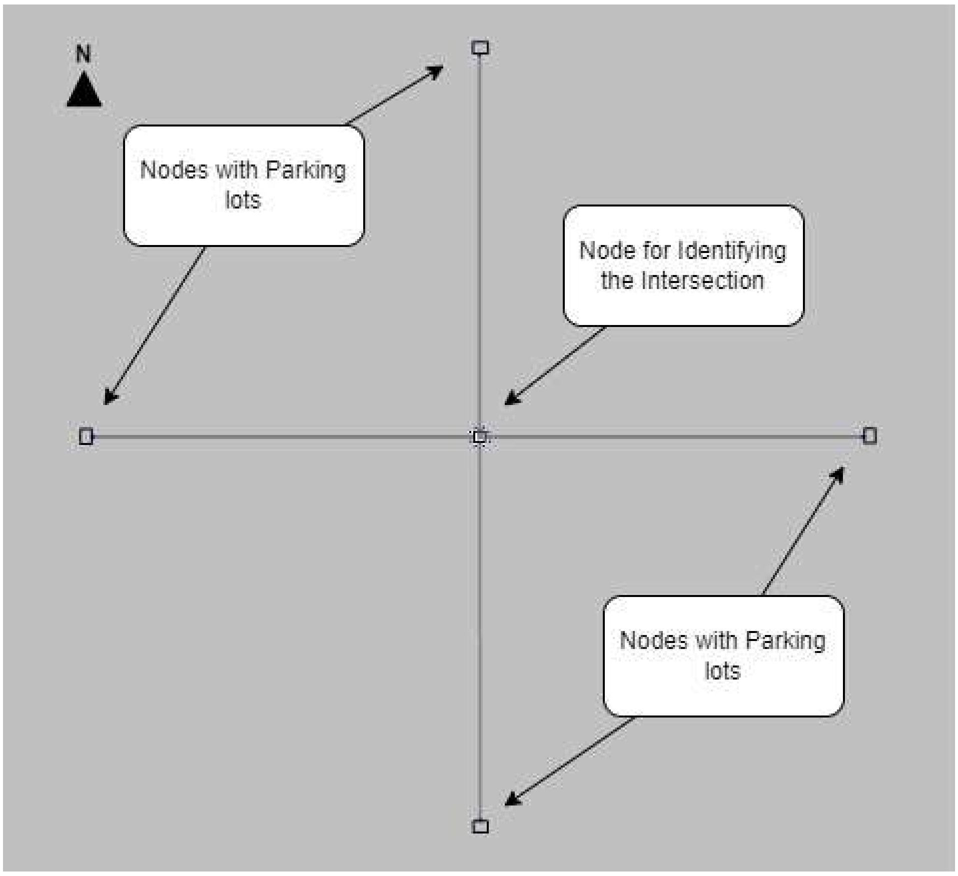


Figure 25: Nodes in the Model.

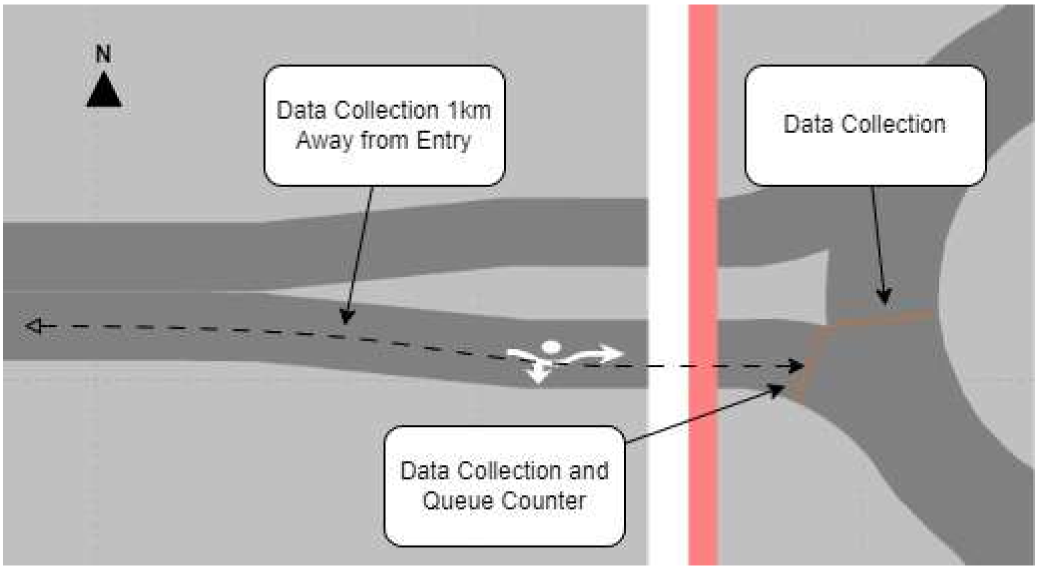


Figure 26: Data Collection Point and Queue Counter Locations.

Appendix C – Simulation

This appendix contains the normality test results with an explanation as well as the OD-matrices.

Appendix C.1. – OD-Matrices

All the OD-matrices used for each entry/opposing ratio scenario can be found in this appendix. The first matrix and last matrix are for 15 minutes as they also contain warmup and cooldown matrices. It should also be noted that the rest of the OD-matrices are used for intervals of 5 minutes.

Table 17: OD-matrices for scenarios using the 25/75 ratio.

OD-Matrix 1

O\D	East	South	West	North	SUM
East		45.00	3.33	3.33	52
South	3.33		3.33	3.33	10
West	15.00	15.00		15.00	45
North	45.00	45.00	3.33		93
SUM	63	105	10	22	200

OD-Matrix 2

O\D	East	South	West	North	SUM
East		16.50	1.11	1.11	19
South	1.11		1.11	1.11	3
West	5.50	5.50		5.50	17
North	16.50	16.50	1.11		34
SUM	23	39	3	8	73

OD-Matrix 3

O\D	East	South	West	North	SUM
East		18.00	1.11	1.11	20
South	1.11		1.11	1.11	3
West	6.00	6.00		6.00	18
North	18.00	18.00	1.11		37
SUM	25	42	3	8	79

OD-Matrix 4

O\D	East	South	West	North	SUM
East		19.50	1.11	1.11	22
South	1.11		1.11	1.11	3
West	6.50	6.50		6.50	20
North	19.50	19.50	1.11		40
SUM	27	46	3	9	85

OD-Matrix 5

O\D	East	South	West	North	SUM
East		21.00	1.11	1.11	23
South	1.11		1.11	1.11	3
West	7.00	7.00		7.00	21
North	21.00	21.00	1.11		43
SUM	29	49	3	9	91

OD-Matrix 6

O\D	East	South	West	North	SUM
East		22.50	1.11	1.11	25

South	1.11		1.11	1.11	3
West	7.50	7.50		7.50	23
North	22.50	22.50	1.11		46
SUM	31	53	3	10	97

OD-Matrix 7

O\D	East	South	West	North	SUM
East		24.00	1.11	1.11	26
South	1.11		1.11	1.11	3
West	8.00	8.00		8.00	24
North	24.00	24.00	1.11		49
SUM	33	56	3	10	103

OD-Matrix 8

O\D	East	South	West	North	SUM
East		25.50	1.11	1.11	28
South	1.11		1.11	1.11	3
West	8.50	8.50		8.50	26
North	25.50	25.50	1.11		52
SUM	35	60	3	11	109

OD-Matrix 9

O\D	East	South	West	North	SUM
East		27.00	1.11	1.11	29
South	1.11		1.11	1.11	3
West	9.00	9.00		9.00	27
North	27.00	27.00	1.11		55
SUM	37	63	3	11	115

OD-Matrix 10

O\D	East	South	West	North	SUM
East		28.50	1.11	1.11	31
South	1.11		1.11	1.11	3
West	9.50	9.50		9.50	29
North	28.50	28.50	1.11		58
SUM	39	67	3	12	121

OD-Matrix 11

O\D	East	South	West	North	SUM
East		30.00	1.11	1.11	32
South	1.11		1.11	1.11	3
West	10.00	10.00		10.00	30
North	30.00	30.00	1.11		61
SUM	41	70	3	12	127

OD-Matrix 12

O\D	East	South	West	North	SUM
East		63.00	2.22	2.22	67
South	2.22		2.22	2.22	7
West	21.00	21.00		21.00	63
North	63.00	63.00	2.22		128
SUM	86	147	7	25	265

Table 18: OD-matrices for scenarios using the 50/50 ratio.

OD-Matrix 1

O\D	East	South	West	North	SUM
East	0	30	3	3	37
South	3	0	3	3	10
West	30	30	0	30	90
North	30	30	3	0	63
SUM	63	90	10	37	200

OD-Matrix 2

O\D	East	South	West	North	SUM
East		11	1	1	13
South	1		1	1	3
West	11	11		11	33
North	11	11	1		23
SUM	23	33	3	13	73

OD-Matrix 3

O\D	East	South	West	North	SUM
East		12	1	1	14
South	1		1	1	3
West	12	12		12	36
North	12	12	1		25
SUM	25	36	3	14	79

OD-Matrix 4

O\D	East	South	West	North	SUM
East		13	1	1	15
South	1		1	1	3
West	13	13		13	39
North	13	13	1		27
SUM	27	39	3	15	85

OD-Matrix 5

O\D	East	South	West	North	SUM
East		14	1	1	16
South	1		1	1	3
West	14	14		14	42
North	14	14	1		29
SUM	29	42	3	16	91

OD-Matrix 6

O\D	East	South	West	North	SUM
East		15	1	1	17
South	1		1	1	3
West	15	15		15	45
North	15	15	1		31
SUM	31	45	3	17	97

OD-Matrix 7

O\D	East	South	West	North	SUM
East		16	1	1	18

South	1		1	1	3
West	16	16		16	48
North	16	16	1		33
SUM	33	48	3	18	103

OD-Matrix 8

O\D	East	South	West	North	SUM
East		17	1	1	19
South	1		1	1	3
West	17	17		17	51
North	17	17	1		35
SUM	35	51	3	19	109

OD-Matrix 9

O\D	East	South	West	North	SUM
East		18	1	1	20
South	1		1	1	3
West	18	18		18	54
North	18	18	1		37
SUM	37	54	3	20	115

OD-Matrix 10

O\D	East	South	West	North	SUM
East		19	1	1	21
South	1		1	1	3
West	19	19		19	57
North	19	19	1		39
SUM	39	57	3	21	121

OD-Matrix 11

O\D	East	South	West	North	SUM
East		20	1	1	22
South	1		1	1	3
West	20	20		20	60
North	20	20	1		41
SUM	41	60	3	22	127

OD-Matrix 12

O\D	East	South	West	North	SUM
East		42	2	2	46
South	2		2	2	7
West	42	42		42	126
North	42	42	2		86
SUM	86	126	7	46	265

Table 19: OD-matrices for scenarios using the 75/25 ratio.

OD-Matrix 1

O\D	East	South	West	North	SUM
East		15.00	3.33	3.33	22

South	3.33		3.33	3.33	10
West	45.00	45.00		45.00	135
North	15.00	15.00	3.33		33
SUM	63	75	10	52	200

OD-Matrix 2

O\D	East	South	West	North	SUM
East		5.50	1.11	1.11	8
South	1.11		1.11	1.11	3
West	16.50	16.50		16.50	50
North	5.50	5.50	1.11		12
SUM	23	28	3	19	73

OD-Matrix 3

O\D	East	South	West	North	SUM
East		6.00	1.11	1.11	8
South	1.11		1.11	1.11	3
West	18.00	18.00		18.00	54
North	6.00	6.00	1.11		13
SUM	25	30	3	20	79

OD-Matrix 4

O\D	East	South	West	North	SUM
East		6.50	1.11	1.11	9
South	1.11		1.11	1.11	3
West	19.50	19.50		19.50	59
North	6.50	6.50	1.11		14
SUM	27	33	3	22	85

OD-Matrix 5

O\D	East	South	West	North	SUM
East		7.00	1.11	1.11	9
South	1.11		1.11	1.11	3
West	21.00	21.00		21.00	63
North	7.00	7.00	1.11		15
SUM	29	35	3	23	91

OD-Matrix 6

O\D	East	South	West	North	SUM
East		7.50	1.11	1.11	10
South	1.11		1.11	1.11	3
West	22.50	22.50		22.50	68
North	7.50	7.50	1.11		16
SUM	31	38	3	25	97

OD-Matrix 7

O\D	East	South	West	North	SUM
East		8.00	1.11	1.11	10
South	1.11		1.11	1.11	3
West	24.00	24.00		24.00	72
North	8.00	8.00	1.11		17
SUM	33	40	3	26	103

OD-Matrix 8

O\D	East	South	West	North	SUM
East		8.50	1.11	1.11	11
South	1.11		1.11	1.11	3
West	25.50	25.50		25.50	77
North	8.50	8.50	1.11		18
SUM	35	43	3	28	109

OD-Matrix 9

O\D	East	South	West	North	SUM
East		9.00	1.11	1.11	11
South	1.11		1.11	1.11	3
West	27.00	27.00		27.00	81
North	9.00	9.00	1.11		19
SUM	37	45	3	29	115

OD-Matrix 10

O\D	East	South	West	North	SUM
East		9.50	1.11	1.11	12
South	1.11		1.11	1.11	3
West	28.50	28.50		28.50	86
North	9.50	9.50	1.11		20
SUM	39	48	3	31	121

OD-Matrix 11

O\D	East	South	West	North	SUM
East		10.00	1.11	1.11	12
South	1.11		1.11	1.11	3
West	30.00	30.00		30.00	90
North	10.00	10.00	1.11		21
SUM	41	50	3	32	127

OD-Matrix 12

O\D	East	South	West	North	SUM
East		21.00	2.22	2.22	25
South	2.22		2.22	2.22	7
West	63.00	63.00		63.00	189
North	21.00	21.00	2.22		44
SUM	86	105	7	67	265

Appendix C.2. – Normality Test

The normality test has been performed using the Jarque-Bera test. This test is a goodness-of-fit test that looks at the skewness and kurtosis to see if it matches a normal distribution (Bobbitt, 2021). The test has been performed for a significance level of 0.05, with the null hypothesis of normality following a Chi-Square distribution with 2 degrees of freedom. The Jarque-Bera test can be seen in Eq. 9, where n is the number of observations, S the skewness and C the kurtosis. These variables have been determined using Excel. The results of the JB test can be seen in Table 20. The entirety of the first ratio scenario has been tested and 6 of these are not normally distributed. However, these have been assumed to be normally distributed.

$$JB = \left(\frac{n}{6}\right) * (S^2 + \left(\frac{C^2}{4}\right)) \qquad \textit{Eq. 9}$$

Table 20: Normality test results.

Scenario	Observations (N)	Sample Skewness	Sample Kurtosis	JB Test Statistics	P-Value
1_0_CV	50	0.6071	-0.3565	3.3363	0.1886
1_0_CV_P	50	-0.0196	-0.8123	1.3780	0.5021
1_0_CV_B	50	-0.0641	0.2831	0.2013	0.9043
1_0_CV_PB	50	0.4706	-0.0462	1.8502	0.3965
1_20_AV_C	50	0.3916	0.4995	1.7975	0.4071
1_20_AV_C_P	50	0.1823	-0.3460	0.5263	0.7686
1_20_AV_C_B	50	0.2811	-0.2390	0.7773	0.6780
1_20_AV_C_PB	50	0.1879	-0.3977	0.6237	0.7321
1_20_AV_N	50	0.4906	0.6899	2.9972	0.2234
1_20_AV_N_P	50	-0.1408	-0.3523	0.4238	0.8090
1_20_AV_N_B	50	-0.4844	0.2903	2.1309	0.3446
1_20_AV_N_PB	50	0.2344	0.4843	0.9465	0.6230
1_20_AV_A	50	0.1419	-0.2381	0.2860	0.8668
1_20_AV_A_P	50	0.5075	-0.0426	2.1500	0.3413
1_20_AV_A_B	50	0.3929	-0.3328	1.5174	0.4683
1_20_AV_A_PB	50	-0.0210	0.6799	0.9666	0.6167
1_40_AV_C	50	0.2877	-0.5359	1.2881	0.5252
1_40_AV_C_P	50	0.2259	-0.1788	0.4917	0.7821
1_40_AV_C_B	50	0.0069	-0.9829	2.0131	0.3655
1_40_AV_C_PB	50	0.1485	-0.0014	0.1838	0.9122
1_40_AV_N	50	0.2852	-0.1959	0.7576	0.6847
1_40_AV_N_P	50	0.3502	-0.1891	1.0963	0.5780
1_40_AV_N_B	50	0.6486	1.0231	5.6858	0.0583
1_40_AV_N_PB	50	0.4766	0.1338	1.9306	0.3809
1_40_AV_A	50	0.6308	0.4495	3.7365	0.1544
1_40_AV_A_P	50	0.6123	0.1584	3.1766	0.2043
1_40_AV_A_B	50	0.3887	-0.5326	1.8503	0.3965

1_40_AV_A_PB	50	0.7201	0.9917	6.3700	0.0414
1_60_AV_C	50	0.0641	-0.8563	1.5620	0.4580
1_60_AV_C_P	50	0.1604	-0.4003	0.5481	0.7603
1_60_AV_C_B	50	0.3095	-0.5517	1.4325	0.4886
1_60_AV_C_PB	50	0.7199	0.2565	4.4560	0.1077
1_60_AV_N	50	0.4825	0.5919	2.6699	0.2632
1_60_AV_N_P	50	0.9581	1.0616	9.9970	0.0067
1_60_AV_N_B	50	0.0023	-0.2658	0.1473	0.9290
1_60_AV_N_PB	50	0.1662	-0.4250	0.6064	0.7384
1_60_AV_A	50	0.8672	1.0287	8.4723	0.0145
1_60_AV_A_P	50	-0.0345	-0.8274	1.4361	0.4877
1_60_AV_A_B	50	-0.2011	-0.8500	1.8419	0.3981
1_60_AV_A_PB	50	0.3299	-0.2887	1.0804	0.5826
1_80_AV_C	50	0.6383	-0.7003	4.4175	0.1098
1_80_AV_C_P	50	0.2236	-0.5288	0.9994	0.6067
1_80_AV_C_B	50	0.7700	0.2637	5.0862	0.0786
1_80_AV_C_PB	50	0.4274	0.0742	1.5337	0.4645
1_80_AV_N	50	0.5508	0.3462	2.7775	0.2494
1_80_AV_N_P	50	1.0915	3.1877	31.0988	0.0000
1_80_AV_N_B	50	0.3146	-0.9012	2.5167	0.2841
1_80_AV_N_PB	50	0.4522	0.2628	1.8477	0.3970
1_80_AV_A	50	0.2793	-0.4261	1.0284	0.5980
1_80_AV_A_P	50	0.3673	-0.8302	2.5603	0.2780
1_80_AV_A_B	50	0.8059	0.9087	7.1329	0.0283
1_80_AV_A_PB	50	0.2978	0.0102	0.7393	0.6910
1_100_AV_C	50	0.2307	-0.0776	0.4560	0.7961
1_100_AV_C_P	50	0.6585	0.2462	3.7393	0.1542
1_100_AV_C_B	50	0.5121	-0.3360	2.4209	0.2981
1_100_AV_C_PB	50	0.2545	-0.3507	0.7958	0.6717
1_100_AV_N	50	0.9570	0.9227	9.4058	0.0091
1_100_AV_N_P	50	0.3160	-0.5995	1.5811	0.4536
1_100_AV_N_B	50	0.2054	-0.4294	0.7357	0.6922
1_100_AV_N_PB	50	0.0013	0.0440	0.0041	0.9980
1_100_AV_A	50	0.6101	-0.1822	3.1711	0.2048
1_100_AV_A_P	50	0.4449	-0.2371	1.7664	0.4135
1_100_AV_A_B	50	0.4934	-0.1201	2.0591	0.3572
1_100_AV_A_PB	50	0.1164	-0.6902	1.1053	0.5754

Appendix D – Entry Capacity CDF

The following appendices are of CDF graphs from every flow ratio scenario. The different vehicle types also have their own graphs, which shows how penetration rate and AV behaviour impact the capacity of scenarios with and without pedestrians and cyclists.

Appendix D.1. – Naming System

This appendix explains how the scenarios are named.

Table 21: Naming system

Example:	1_	20_	AV_C	_P
Name:	RATIO_	AVPR_	VehType	_CROSSING
RATIO_	Entry/Opposing flow ratio			
1_	25/75			
2_	50/50			
3_	75/25			
AVPR_	AV Penetration Rate			
0_	0%			
20_	20%			
40_	40%			
60_	60%			
80_	80%			
100_	100%			
VehType	Vehicle types			
CV	Conventional vehicles			
AV_C	Cautious AVs			
AV_N	Normal AVs			
AV_A	Aggressive AVs			
***_CROSSING**	Enable crossings			
_P	Pedestrian			
_B	Cyclist			
_PB	Pedestrian and Cyclist			
*if empty crossings are disabled				

Appendix D.2. – Base CDF Graphs

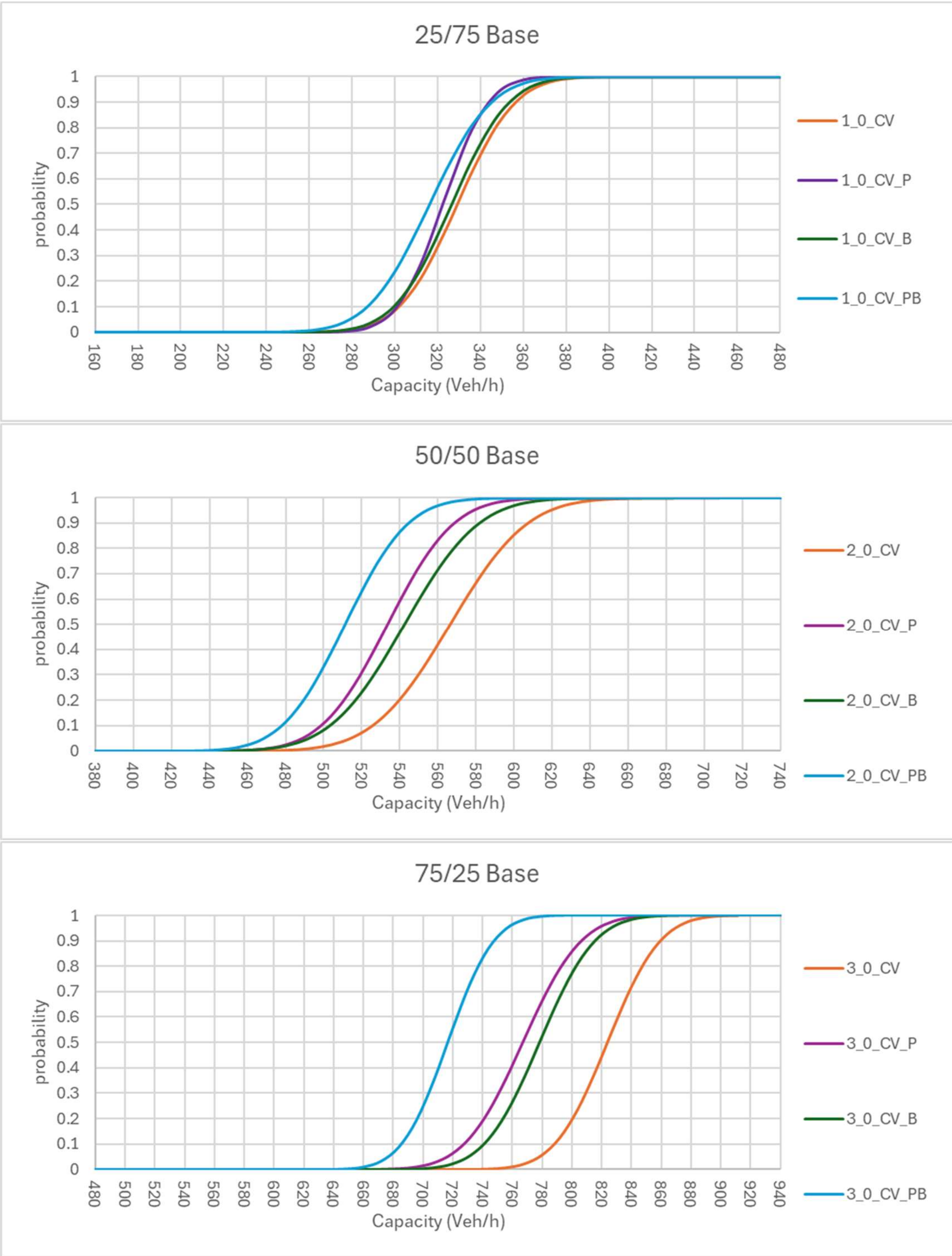


Figure 27: CDF Graphs of CV Scenarios for every Entry/Opp. ratio.

Appendix D.3. – 25/75 CDF Graphs

Cautious, Normal, and Aggressive AVs without Pedestrians and Cyclists

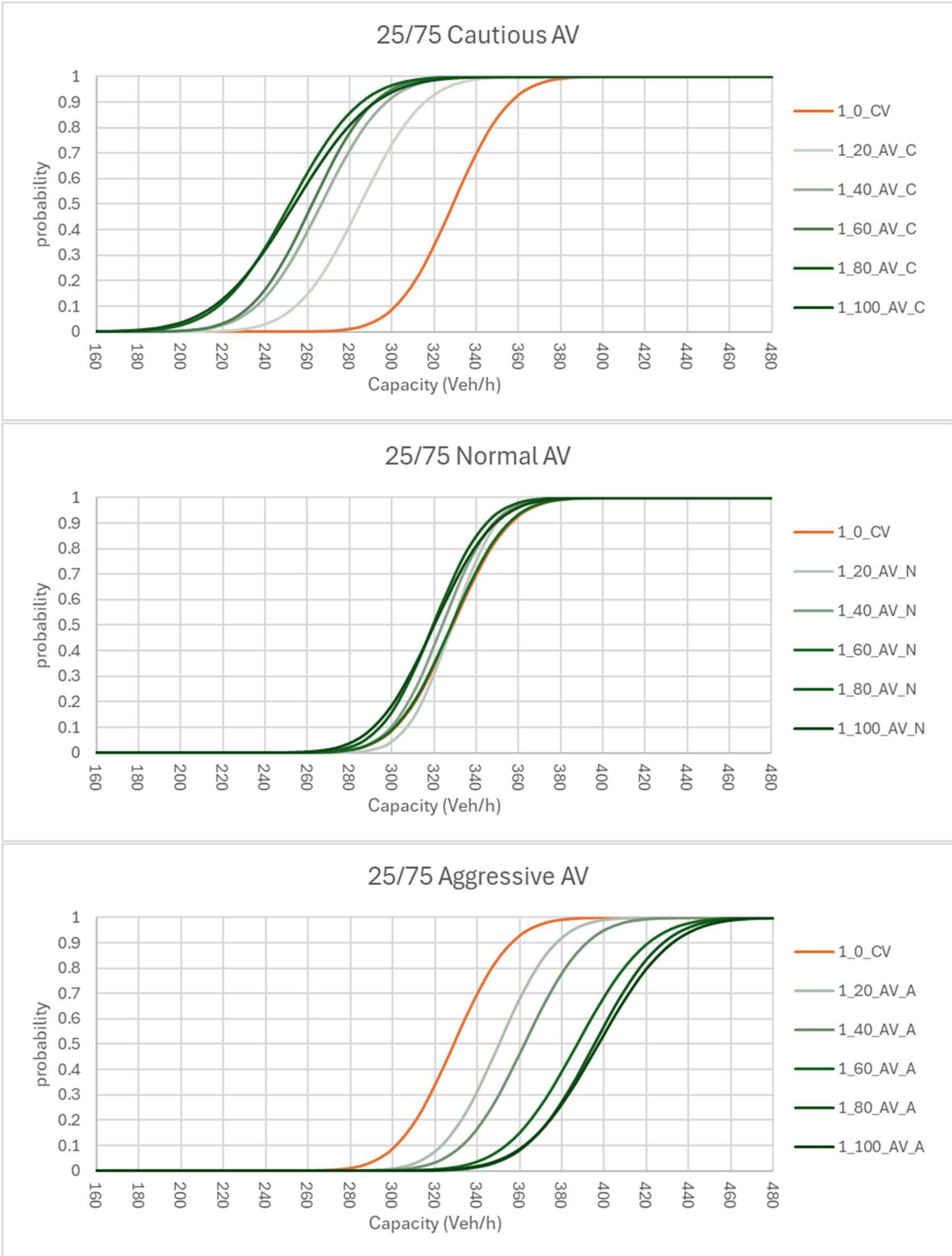


Figure 28: CDF Graphs of AVs for 25/75 Entry/Opp. ratio.

Cautious, Normal, and Aggressive AVs with Pedestrians

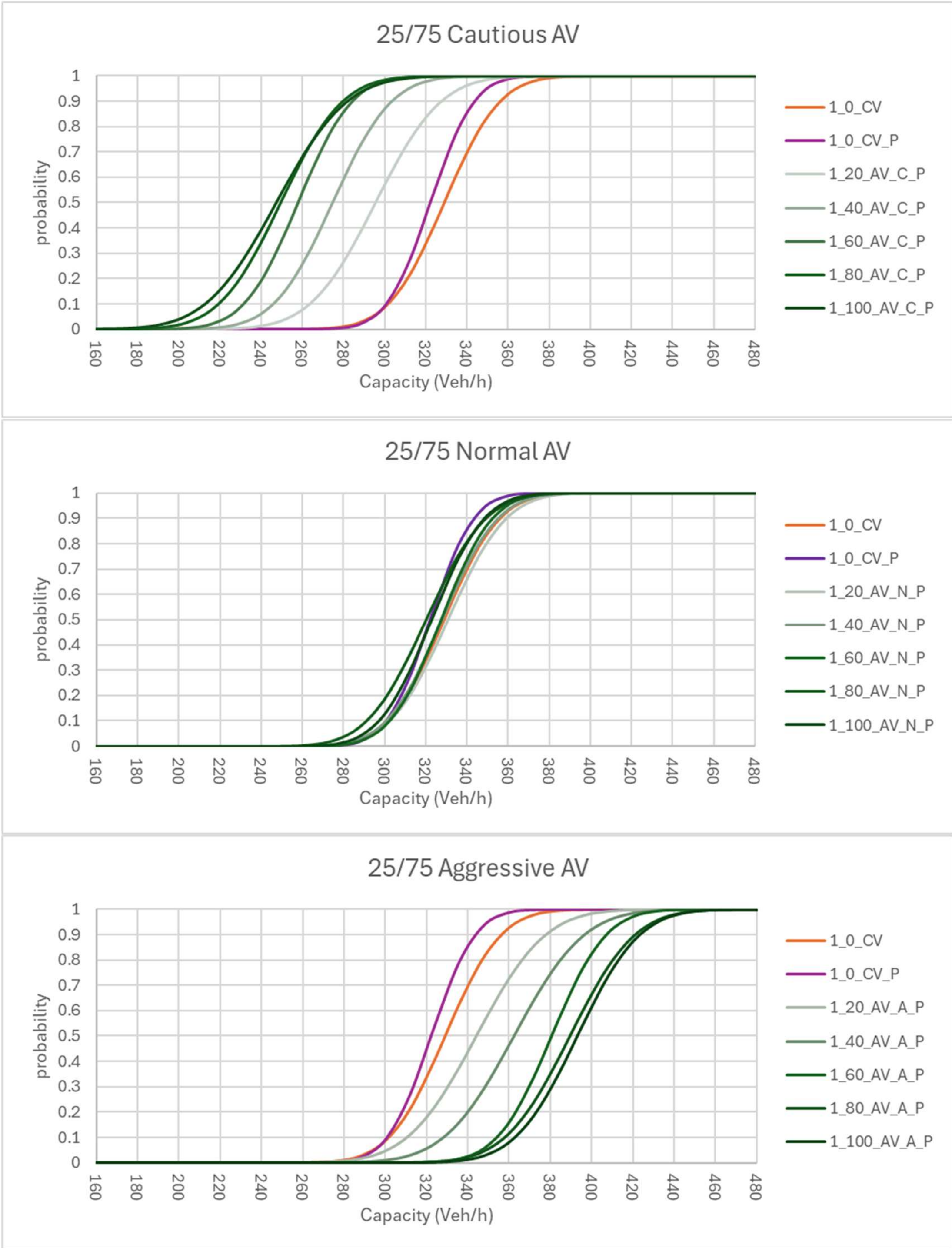


Figure 29: CDF Graphs of AVs for 25/75 Entry/Opp. ratio, with pedestrians.

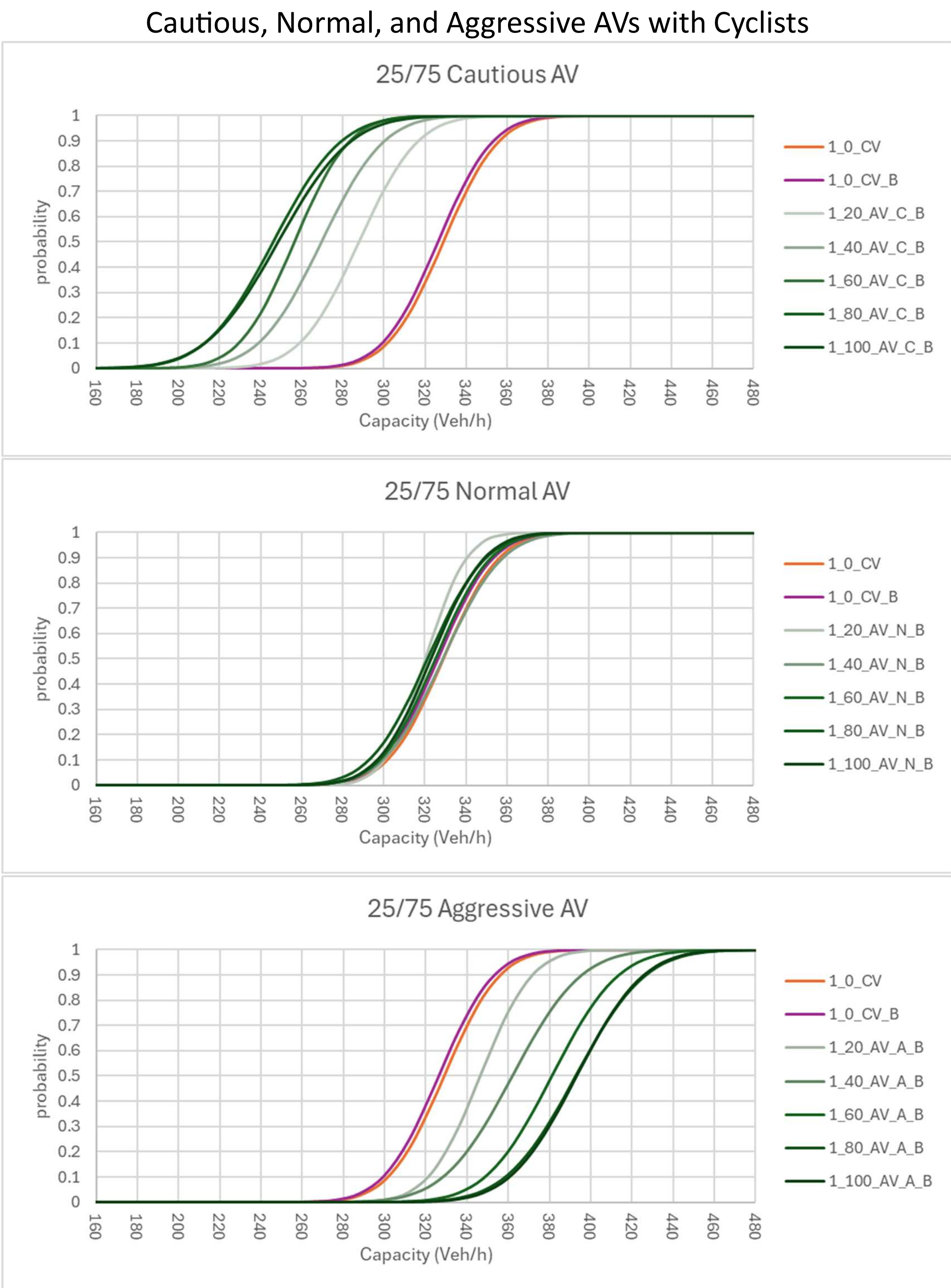


Figure 30: CDF Graphs of AVs for 25/75 Entry/Opp. ratio, with cyclists.

Cautious, Normal, and Aggressive AVs with Pedestrians and Cyclists

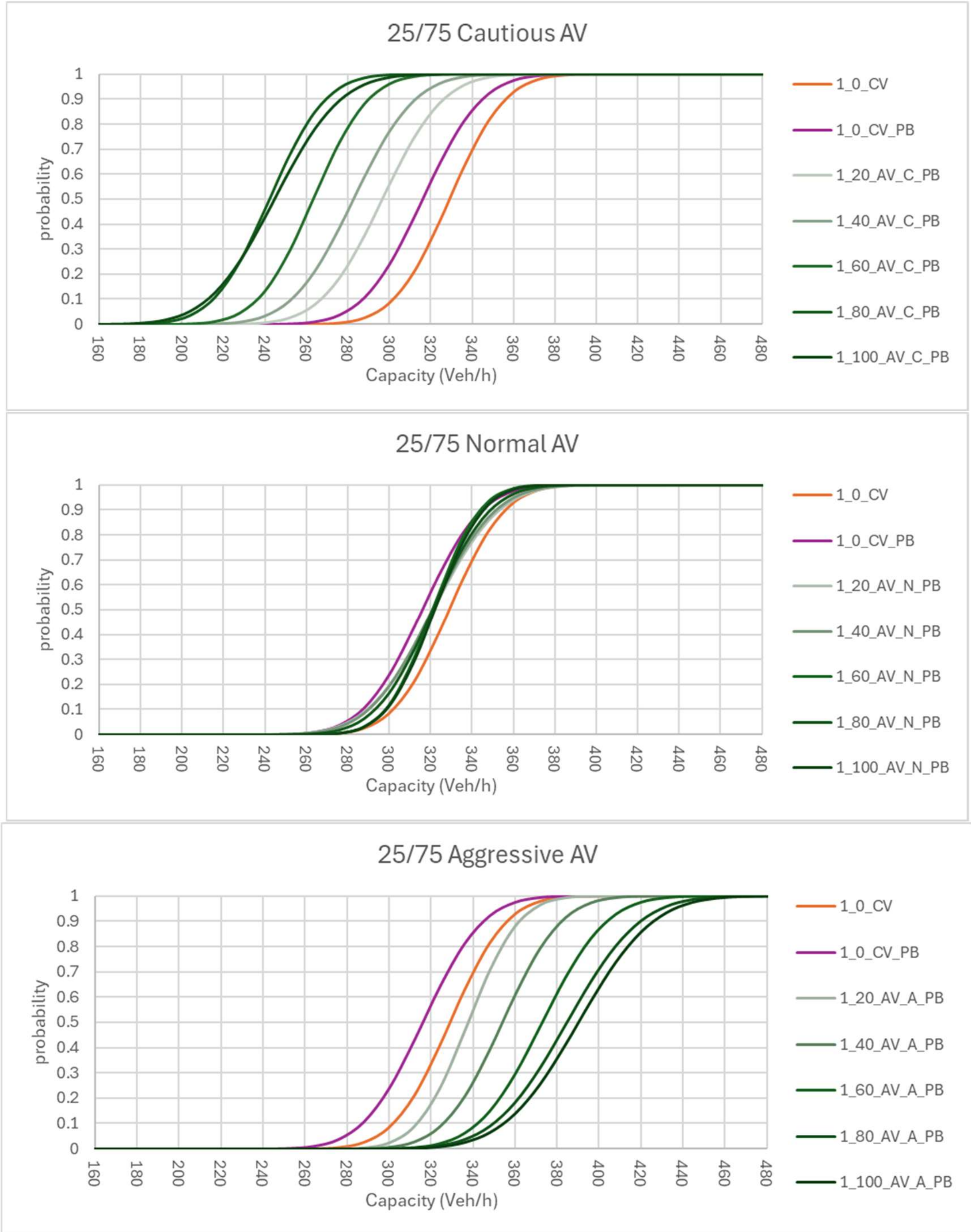


Figure 31: CDF Graphs of AVs for 25/75 Entry/Opp. ratio, with pedestrians and cyclists.

Appendix D.4. – 50/50 CDF Graphs

Cautious, Normal, and Aggressive AVs without Pedestrians and Cyclists

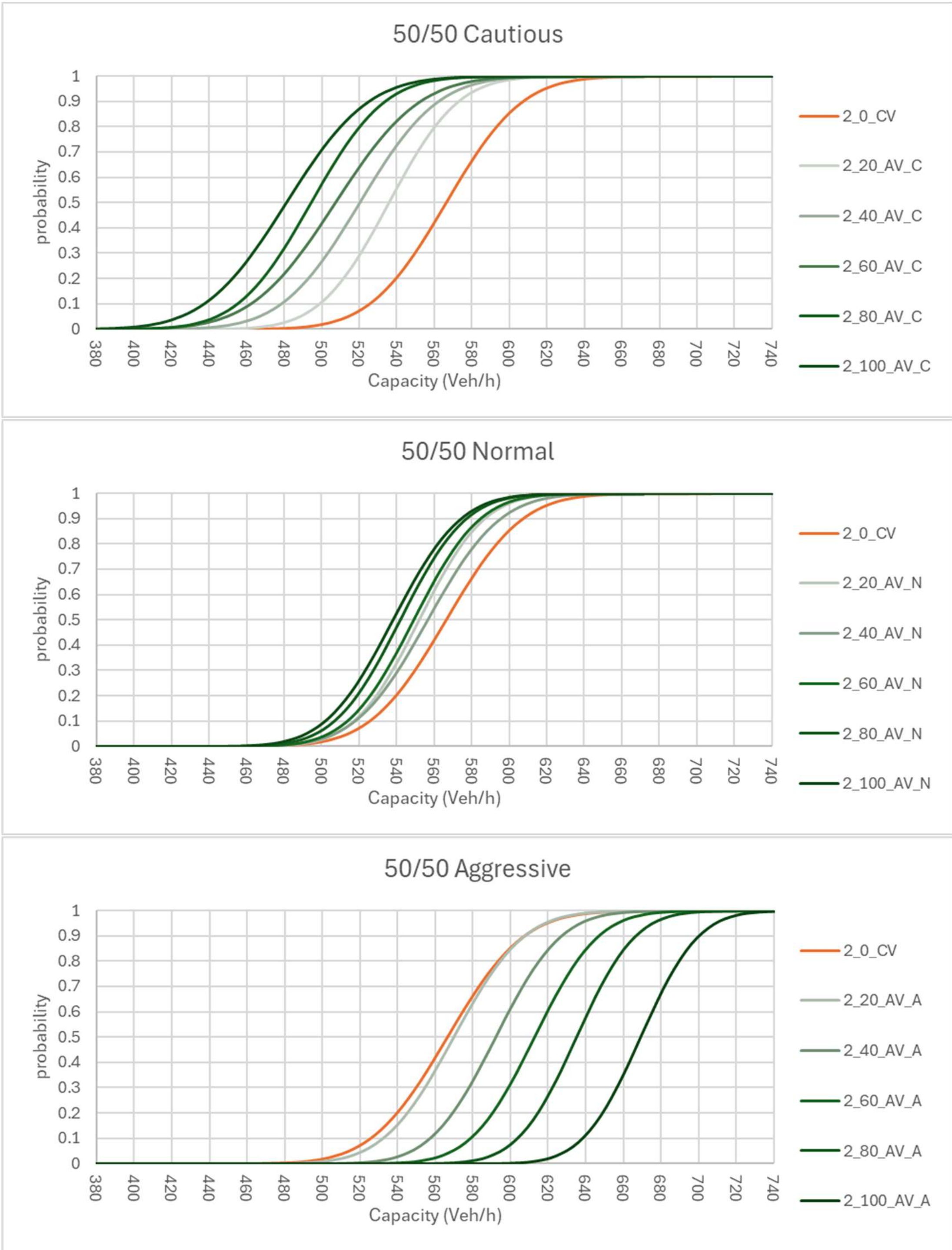


Figure 32: CDF Graphs of AVs for 50/50 Entry/Opp. ratio.

Cautious, Normal, and Aggressive AVs with Pedestrians

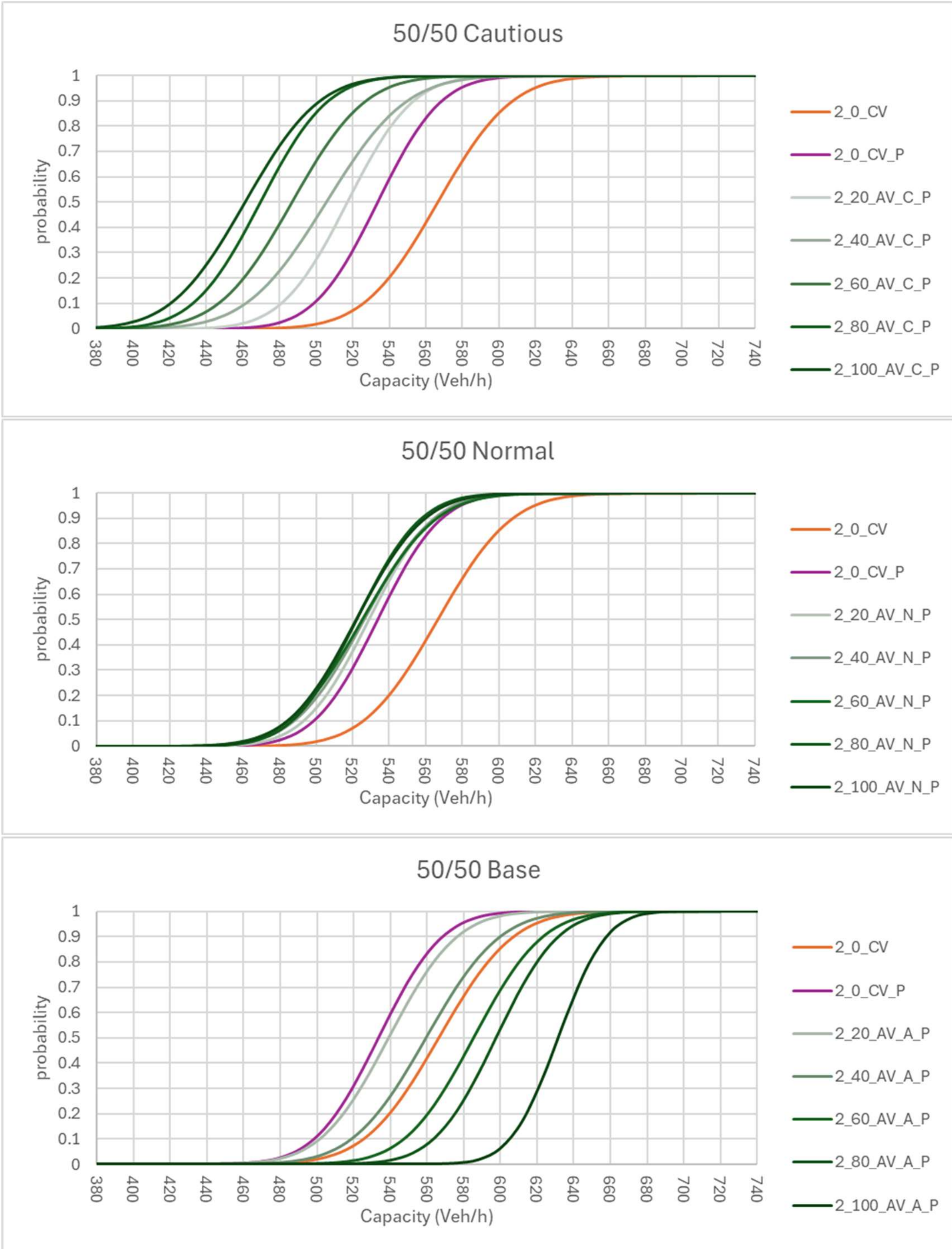


Figure 33: CDF Graphs of AVs for 50/50 Entry/Opp. ratio, with pedestrians.

Cautious, Normal, and Aggressive AVs with Cyclists

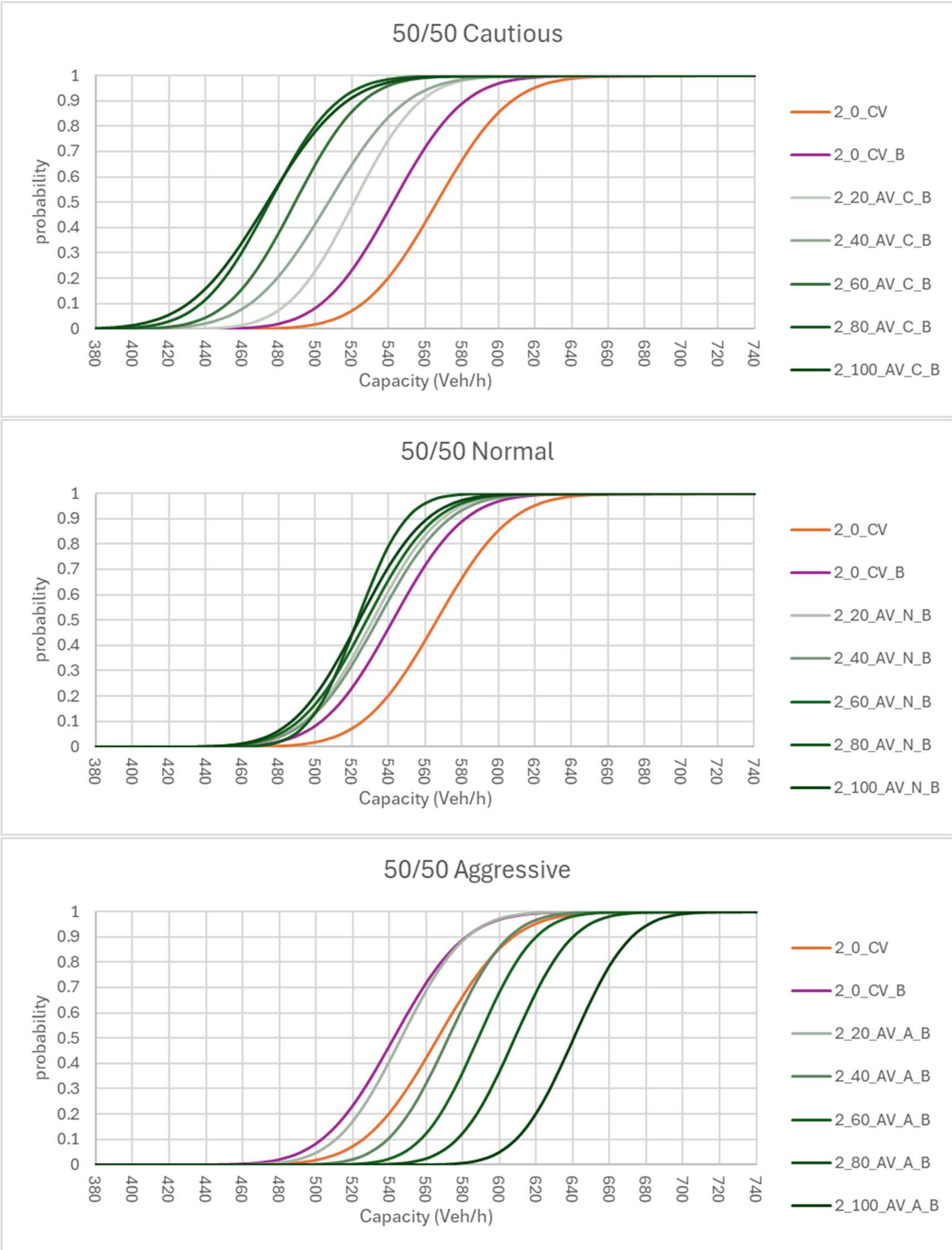


Figure 34: CDF Graphs of AVs for 50/50 Entry/Opp. ratio, with cyclists.

Cautious, Normal, and Aggressive AVs with Pedestrians and Cyclists

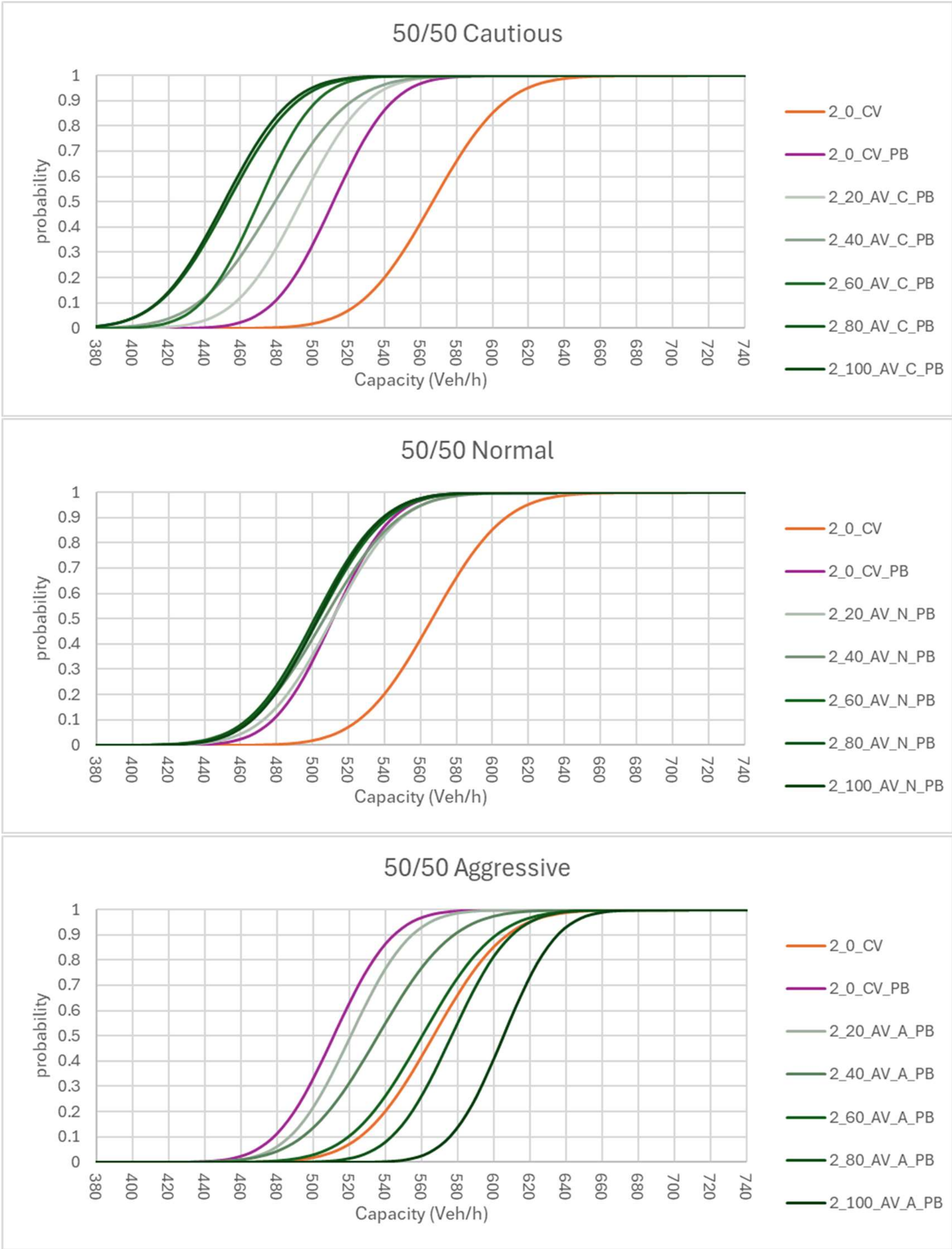


Figure 35: CDF Graphs of AVs for 50/50 Entry/Opp. ratio, with pedestrians and cyclists.

Appendix D.5. – 75/25 CDF Graphs

Cautious, Normal, and Aggressive AVs without Pedestrians and Cyclists

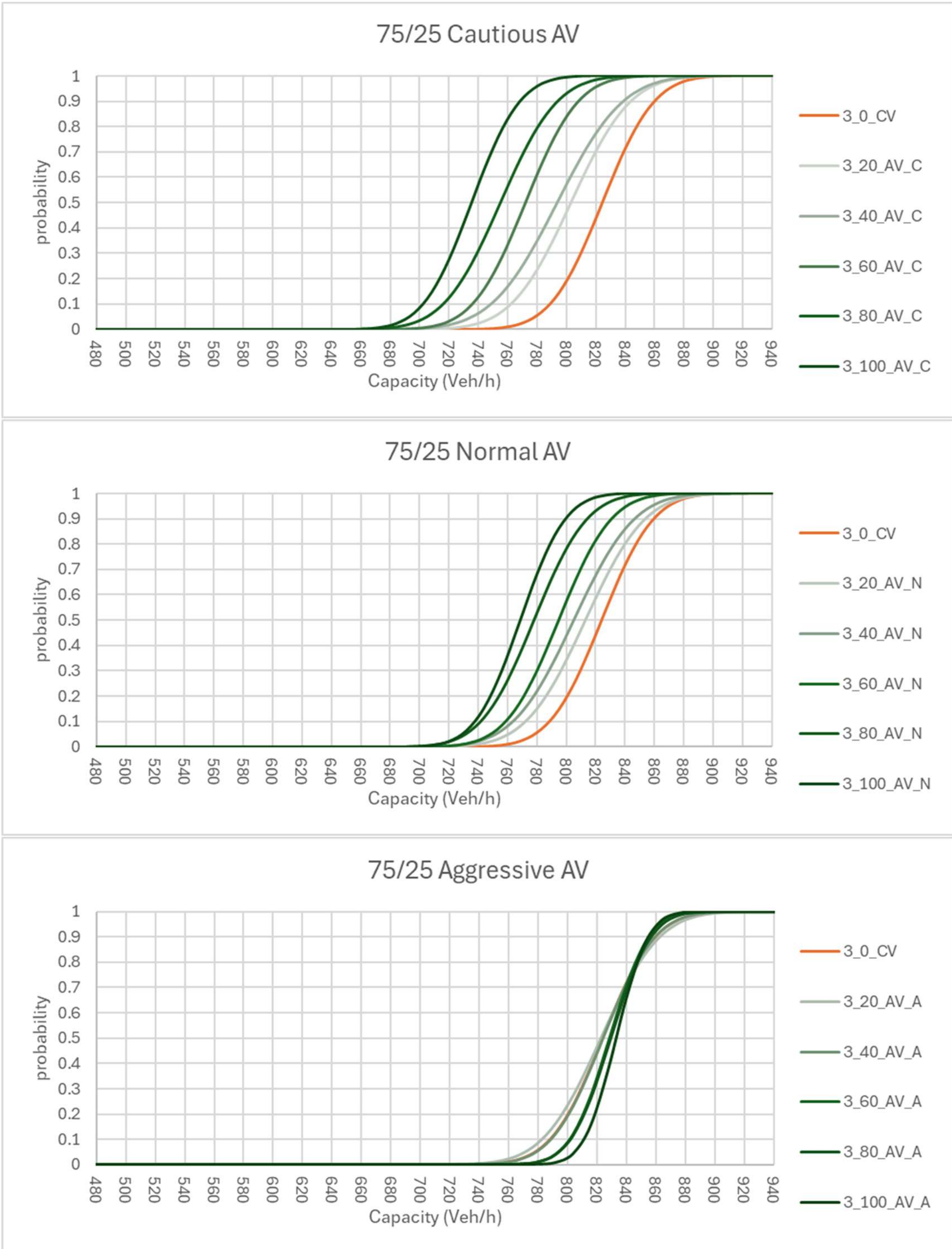


Figure 36: CDF Graphs of AVs for 75/25 Entry/Opp. ratio.

Cautious, Normal, and Aggressive AVs with Pedestrians

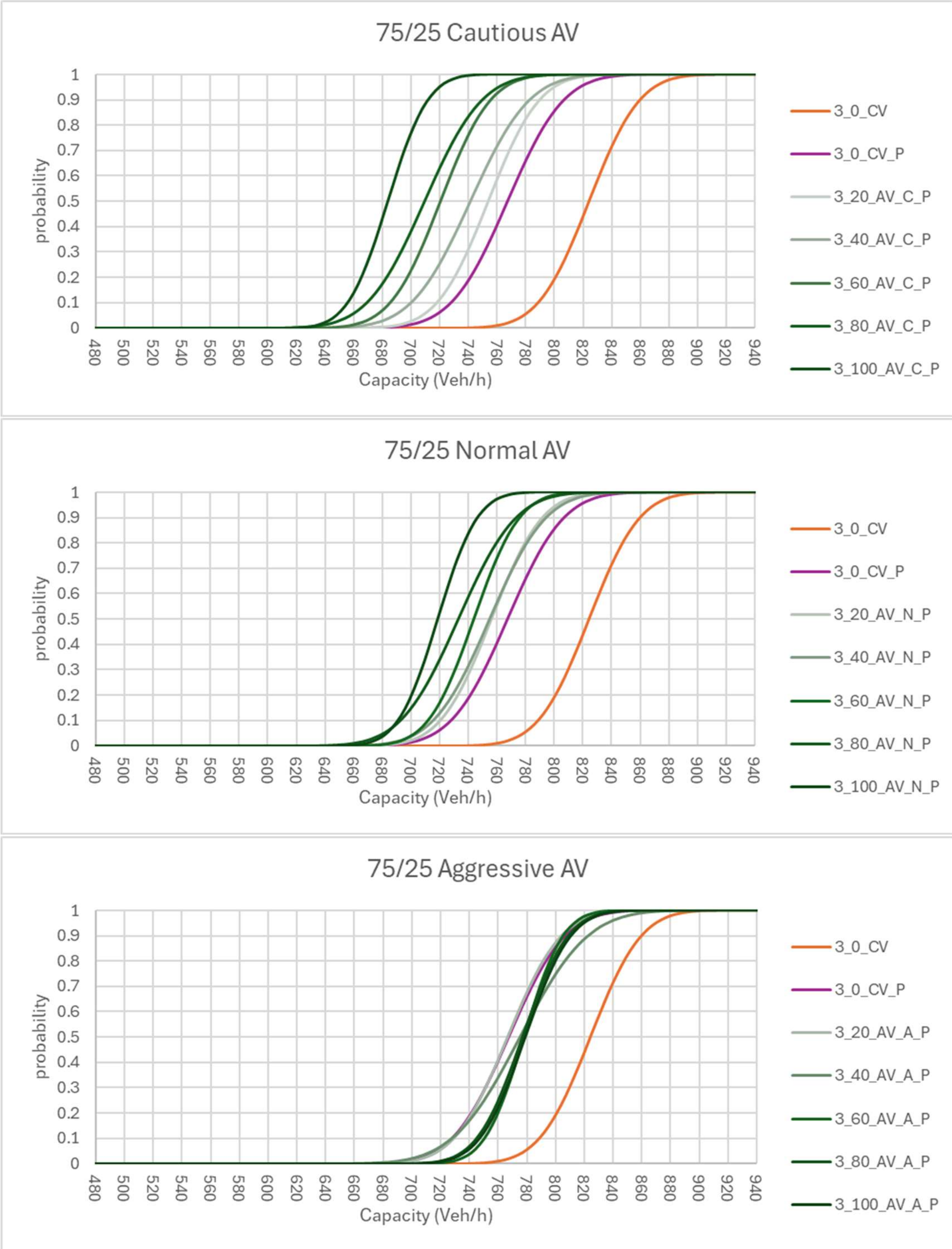


Figure 37: CDF Graphs of AVs for 75/25 Entry/Opp. ratio, with pedestrians.

Cautious, Normal, and Aggressive AVs with Cyclists

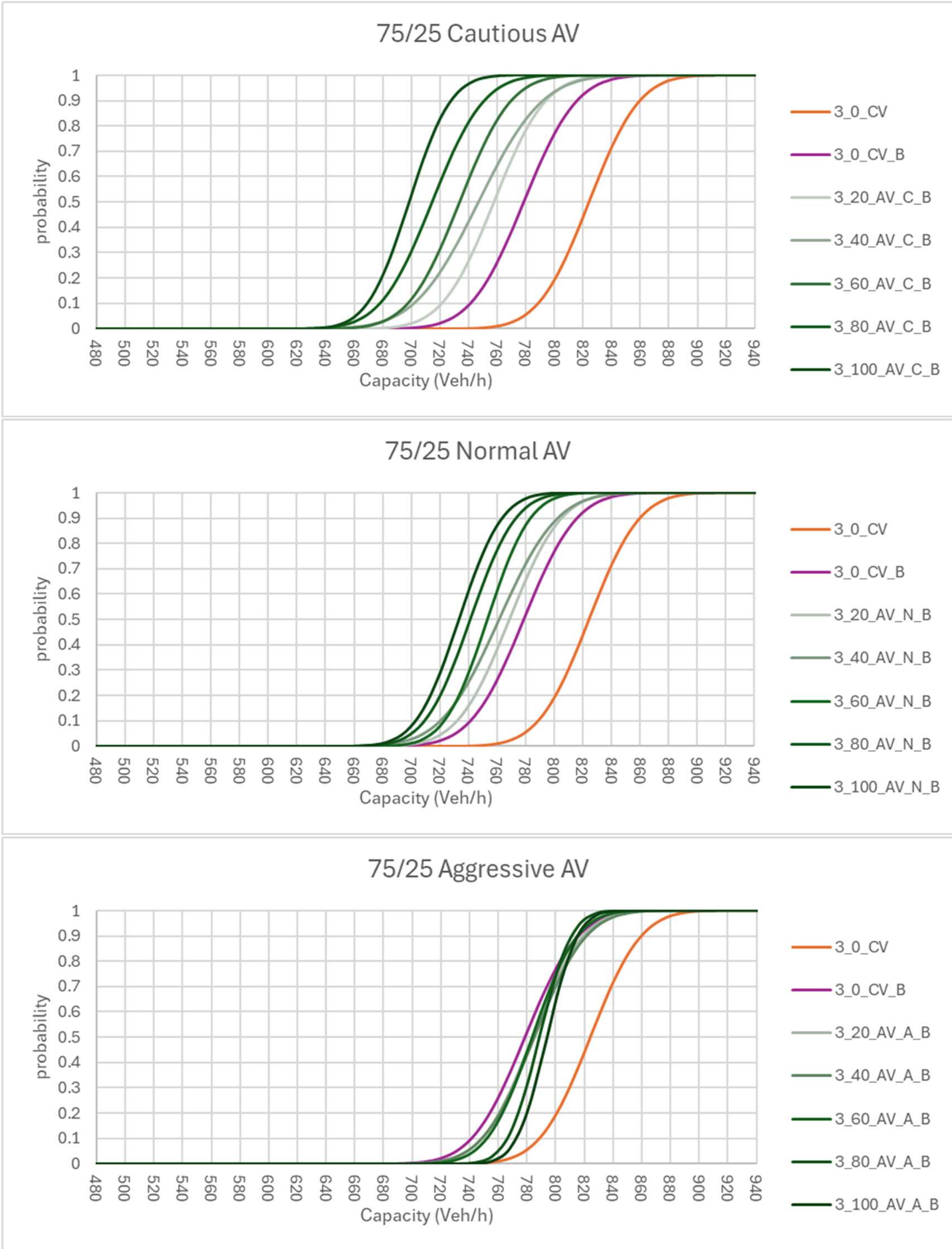


Figure 38: CDF Graphs of AVs for 75/25 Entry/Opp. ratio, with cyclists.

Cautious, Normal, and Aggressive AVs with Pedestrians and Cyclists

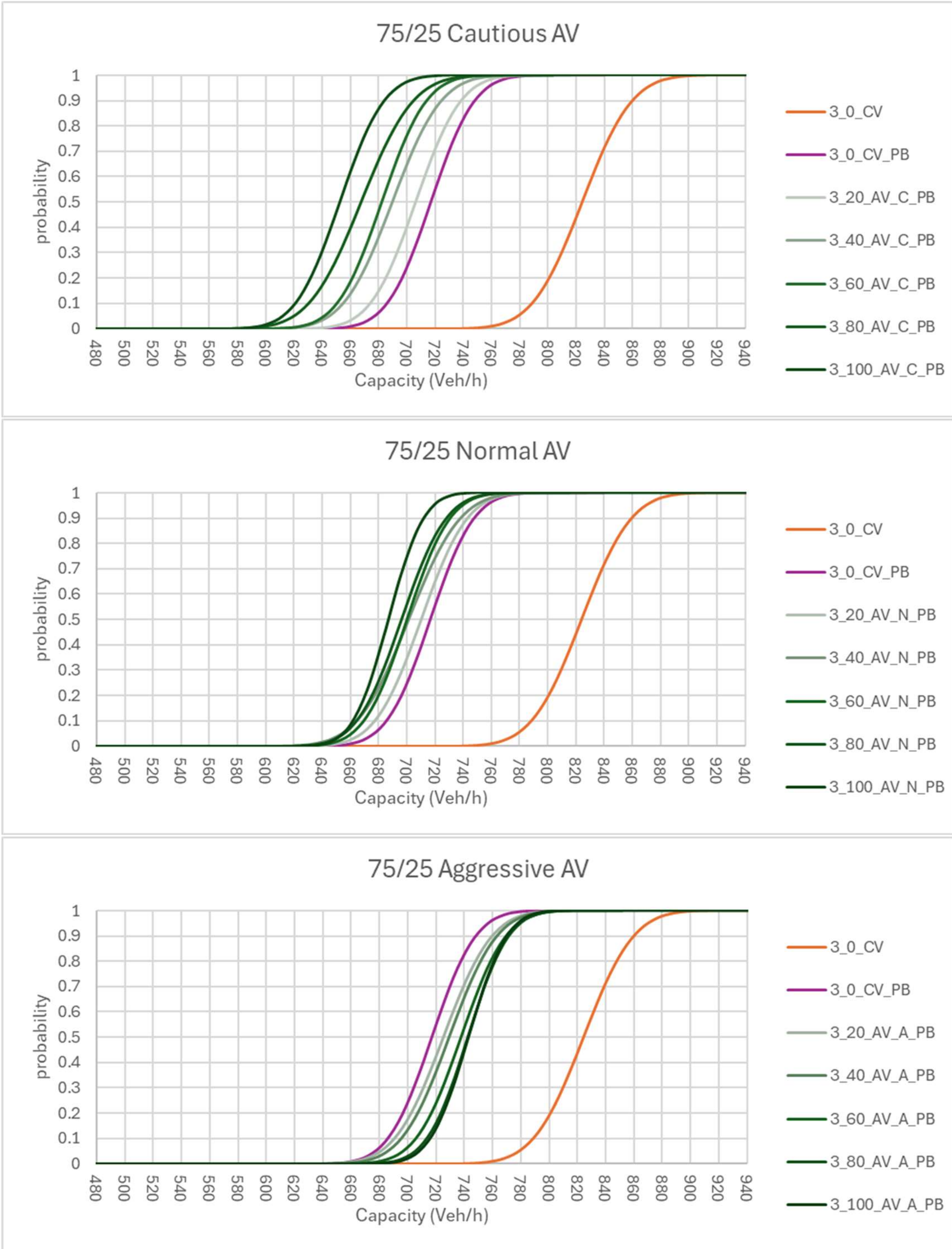
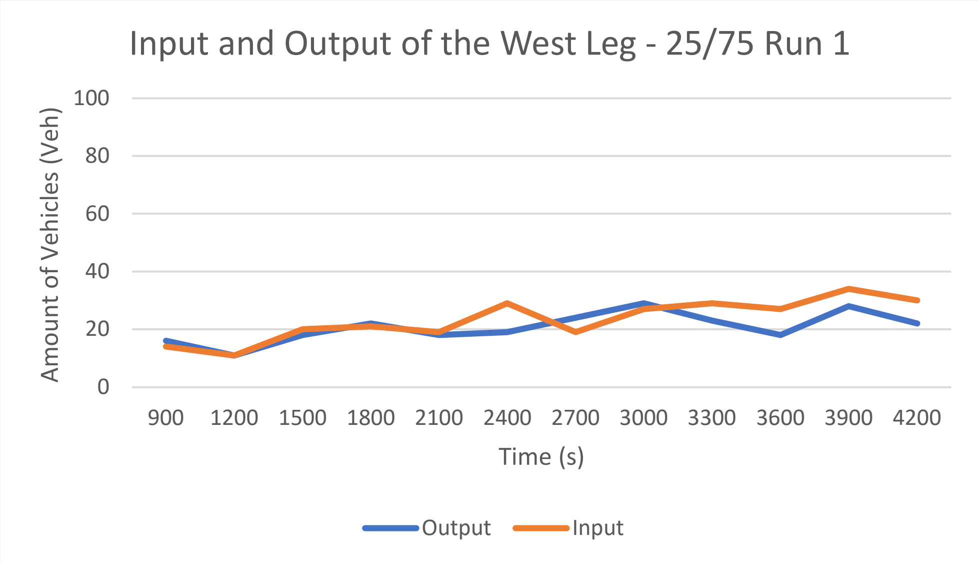
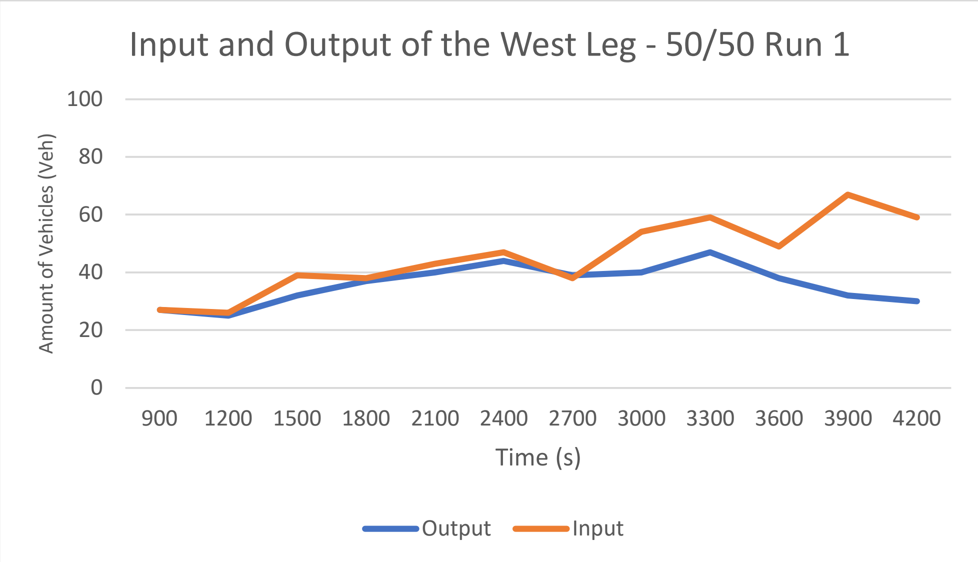


Figure 39: CDF Graphs of AVs for 75/25 Entry/Opp. ratio, with pedestrians and cyclists.

Appendix E – Observations Run 1





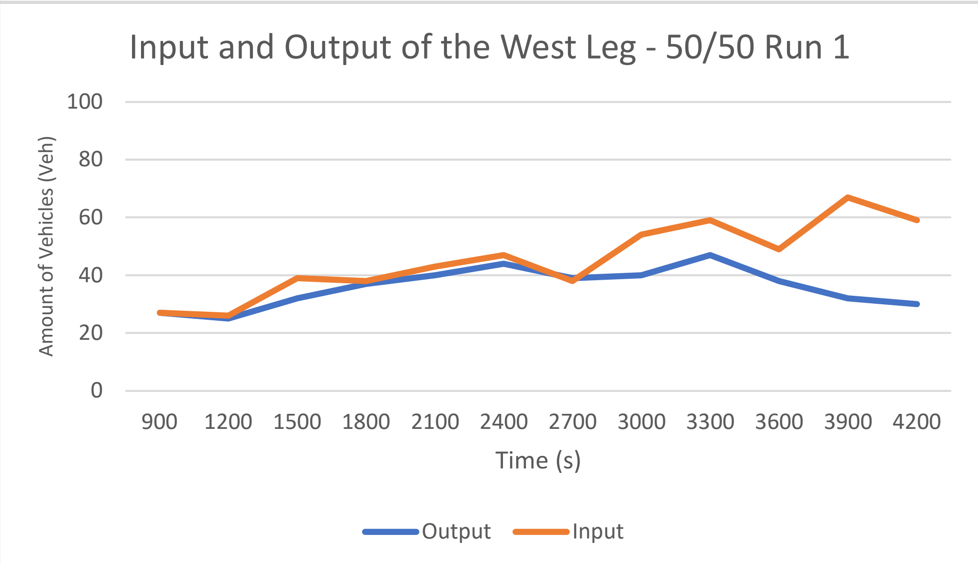


Figure 40: Input and Output of the West leg run 1 for every ratio.

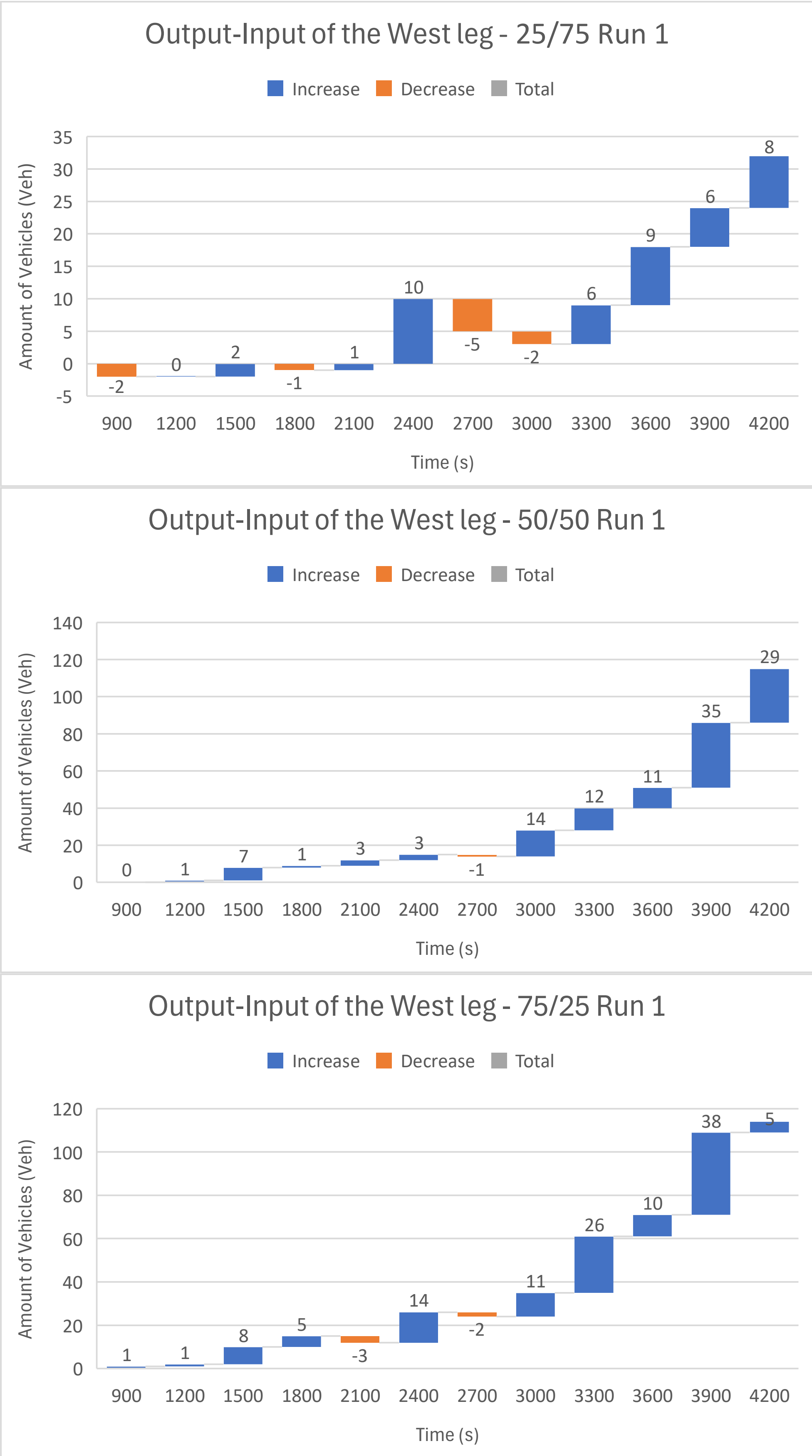


Figure 41: Output-Input of the West leg run 1 for every ratio.

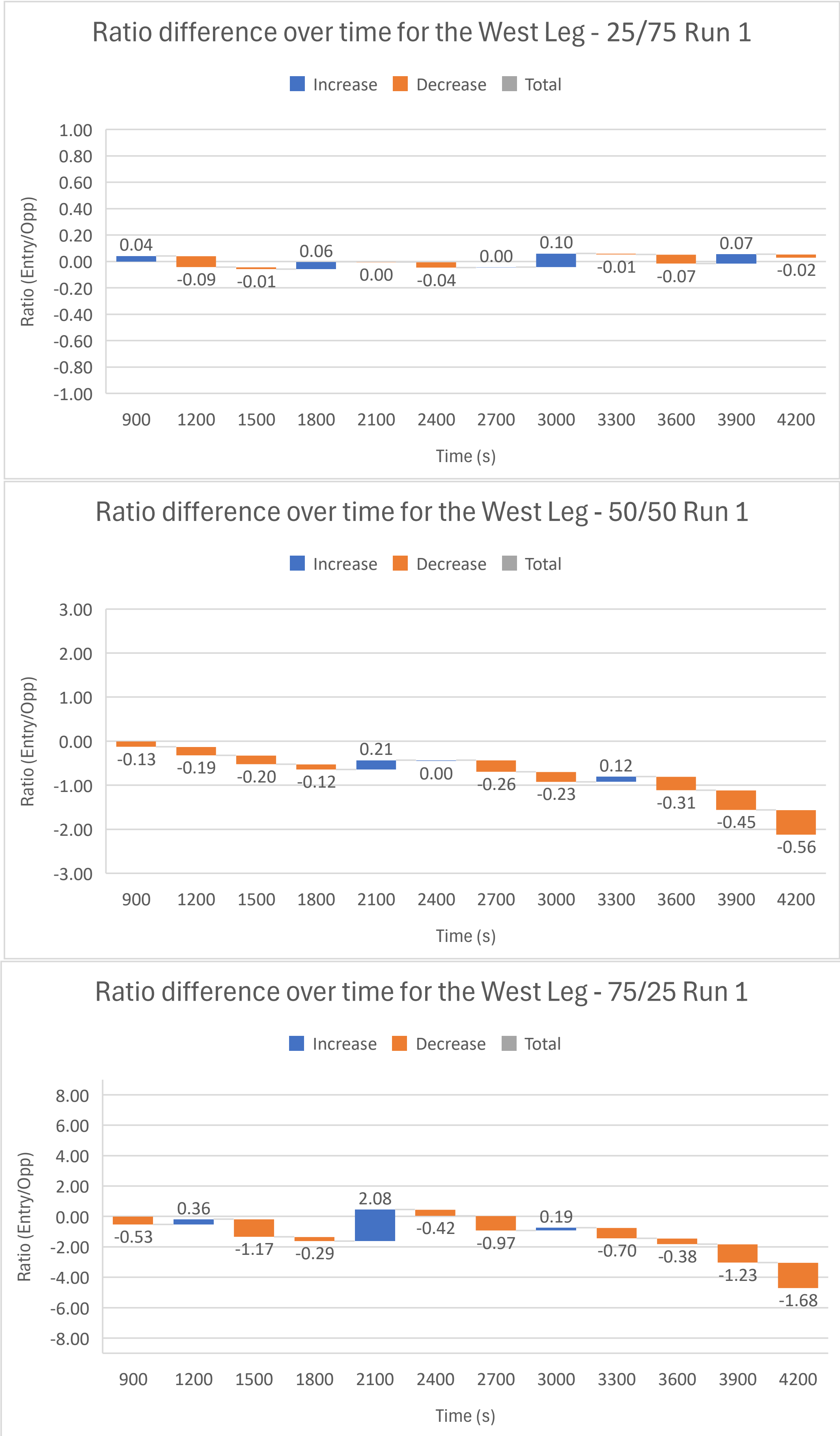


Figure 42: Ratio difference over time for the West leg run 1 for every ratio

Appendix F – Capacity

Table 22: Capacity values.

Name	25/75		50/50		75/25	
	Capacity	Change	Capacity	Change	Capacity	Change
	Veh	%	Veh	%	Veh	%
0_CV	329	0.0	566	0.0	824	0.0
0_CV_P	322	-2.0	534	-5.8	767	-6.9
0_CV_B	326	-0.8	542	-4.2	779	-5.5
0_CV_PB	316	-3.9	511	-9.7	717	-13.0
20_AV_C	285	-13.3	536	-5.4	803	-2.6
20_AV_C_P	296	-10.1	517	-8.7	754	-8.5
20_AV_C_B	288	-12.5	521	-8.0	758	-8.1
20_AV_C_PB	297	-9.8	493	-12.9	706	-14.3
20_AV_N	329	-0.1	552	-2.5	813	-1.3
20_AV_N_P	331	0.6	529	-6.7	756	-8.3
20_AV_N_B	320	-2.6	531	-6.2	768	-6.8
20_AV_N_PB	321	-2.3	511	-9.8	710	-13.8
20_AV_A	350	6.5	570	0.6	823	-0.1
20_AV_A_P	344	4.6	539	-4.8	767	-7.0
20_AV_A_B	347	5.3	546	-3.5	784	-4.9
20_AV_A_PB	338	2.6	521	-8.1	725	-12.0
40_AV_C	267	-19.0	520	-8.1	793	-3.7
40_AV_C_P	275	-16.5	505	-10.8	741	-10.0
40_AV_C_B	270	-18.0	507	-10.5	747	-9.4
40_AV_C_PB	283	-14.1	479	-15.5	690	-16.3
40_AV_N	324	-1.5	557	-1.7	805	-2.3
40_AV_N_P	328	-0.3	526	-7.1	755	-8.4
40_AV_N_B	329	-0.1	534	-5.7	761	-7.6
40_AV_N_PB	321	-2.5	506	-10.6	702	-14.9
40_AV_A	362	10.1	592	4.5	824	0.0
40_AV_A_P	362	10.1	559	-1.2	775	-5.9
40_AV_A_B	362	10.1	572	1.0	785	-4.7
40_AV_A_PB	354	7.6	536	-5.4	729	-11.5
60_AV_C	262	-20.3	507	-10.4	772	-6.3
60_AV_C_P	258	-21.6	487	-14.1	720	-12.6
60_AV_C_B	257	-22.0	489	-13.7	734	-11.0
60_AV_C_PB	263	-20.0	470	-17.0	682	-17.2
60_AV_N	328	-0.2	549	-3.1	795	-3.6
60_AV_N_P	328	-0.4	525	-7.3	744	-9.8
60_AV_N_B	325	-1.2	528	-6.8	753	-8.6
60_AV_N_PB	321	-2.4	503	-11.1	700	-15.0
60_AV_A	387	17.7	613	8.2	829	0.6
60_AV_A_P	381	15.7	585	3.3	778	-5.6
60_AV_A_B	381	15.9	588	3.9	784	-4.9

60_AV_A_PB	373	13.3	560	-1.1	738	-10.5
80_AV_C	252	-23.5	494	-12.7	755	-8.4
80_AV_C_P	250	-24.1	469	-17.1	709	-13.9
80_AV_C_B	246	-25.2	475	-16.1	714	-13.3
80_AV_C_PB	242	-26.4	453	-20.1	667	-19.0
80_AV_N	320	-2.8	542	-4.3	778	-5.6
80_AV_N_P	320	-2.6	522	-7.8	733	-11.1
80_AV_N_B	321	-2.3	523	-7.7	741	-10.1
80_AV_N_PB	321	-2.4	501	-11.5	696	-15.5
80_AV_A	396	20.2	635	12.1	830	0.7
80_AV_A_P	390	18.4	598	5.5	777	-5.7
80_AV_A_B	393	19.4	608	7.4	789	-4.3
80_AV_A_PB	385	16.9	576	1.8	742	-9.9
100_AV_C	254	-22.8	481	-15.0	735	-10.8
100_AV_C_P	247	-24.8	461	-18.6	684	-17.0
100_AV_C_B	249	-24.4	474	-16.4	698	-15.3
100_AV_C_PB	245	-25.7	451	-20.4	652	-20.9
100_AV_N	320	-2.7	538	-5.0	769	-6.7
100_AV_N_P	323	-1.8	522	-7.9	719	-12.8
100_AV_N_B	323	-1.8	524	-7.5	733	-11.0
100_AV_N_PB	322	-2.1	503	-11.2	687	-16.6
100_AV_A	397	20.8	669	18.1	833	1.1
100_AV_A_P	393	19.5	631	11.5	779	-5.5
100_AV_A_B	393	19.5	641	13.1	794	-3.7
100_AV_A_PB	390	18.6	605	6.9	743	-9.9