The Influence of Intersection Strategies of Autonomous Terminal Tractor-Only Intersections on the Productivity of an RTG-based Container Terminal

Thomas Nooyens

Delft University of Technology

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A Simulation Case Study at Portwise

by

Thomas Nooyens

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Thesis committee:	Prof. Dr. ir. R.R. Negenborn	TU Delft, Chair
	Dr. ir. A.J. van Binsbergen	TU Delft, Supervisor
	ir. M.B. Duinkerken	TU Delft, Supervisor
	ir. G.J. Bast	Portwise, Commissioner

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Preface

Hi!

If you are reading this, I would like to welcome you to the most extensive collection of text that I have written until now, and probably also which I will ever write. In this text, or Thesis as it is often referred to, I will take you on an exiting journey of learning about container terminals and ATTs, to making a whole simulation about them, to running experiments with these simulations, and more.

Though I might be doing (or have done dependant on when you are reading this) the study program of Transport, Infrastructure and Logistics, I had nearly no knowledge about anything container terminal related before starting this project one year ago. I also had no idea what an ATT or Autonomous Terminal Tractor was. The one thing I was convinced of, was that autonomous vehicles are awesome, and that I would love to contribute to the further advancement of these vehicles, in order to eventually eradicate human-driven-non-human-powered vehicles from the face of this earth!

As my brain did not contain most of the needed prior knowledge, I had to learn most things during my graduation internship at Portwise. Here my colleagues and fellow interns have made it possible to acquire the necessary information and practice with the simulation program, as well as made it a pleasant and fun environment for me to work in. Though special thanks here go to Gijsbert Bast, who has guided me through the wonderful though very complex world of TIMESQUARE simulations, whose daily advice was invaluable during the treacherous bug fixing months and who was just a joy to have as mentor.

While on the topic of thanking guiding figures, I would like to thank the members of my thesis committee, Mark Duinkerken and Arjan van Binsbergen who have guided me through the entire Thesis project from the TU Delft side, and have helped me to bring structure to my work, as well as helping me with all of the questions and uncertainties that I had during this project. I would also like to thank the chair of my thesis committee, Rudy Negenborn for his scientific guidance and reassurance when things in the project were going well.

Though most of all I would like to thank my family and especially my mother Petra. You have all provided me with a caring and solid foundation from which I could grow into the (if I do say so myself awesome, and humble) person that I am today. You have instilled into me to be curious about the world and about how things work. Without you all, I would have never had the inspiration or drive to become an engineer.

So, now it is time for some last bits of silliness, as the following 135 pages will be completely devoid of it. That said, I do want to issue a small apology to anyone who wants or has to read the full extent of this Thesis, as I might have been a little bit to enthusiastic with including content.
Also fun fact, the term ATT is featured a total of 1161 times in this thesis (this is including its use in tables but excluding figures), which averages out to about 8.6 ATTs per page.

I wanted to close this preface with a quote, and the recent marathon of the Paris Olympics have provided me with one which has stuck to me like peanut butter:

”Mijn moeder zei altijd: Je zaait wat je oogst”
Sifan Hassan, 2024

Thomas Nooyens
Delft, August 2024

Summary

In the world of container terminals, autonomous terminal tractors (ATTs) are currently being developed as a driverless alternative to human-driven terminal tractors (TTs). Unlike traditional automated guided vehicles (AGVs) found in container terminals, ATTs are equipped with sensor packages which allows them to reliably detect other vehicles, and as such they are able to operate in mixed traffic with human driven vehicles (HDVs). This way, ATTs can be implemented into existing rubber tired gantry (RTG)-based container terminals, which have human driven road trucks on the terminal road network.

The RTG-based container terminal used as a base for this study, is a terminal where RTGs and ATTs are used as equipment for the transportation of containers within the terminal, and which typically features a parallel layout. Here, the ATTs are the only non-human controlled vehicles on the terminal, and are used to facilitate the horizontal transport of containers between the RTGs and the quay cranes (QCs). For this study, ATTs only interact with RTGs and QCs when they exchange containers, as the horizontal movements of RTG and QC which would happen in real life, is left out of scope. ATTs have the most interactions with other ATTs, as they can interact with each-other at every point on the terminal road network. They also have interactions with road trucks on some terminal roads, but not on the quay road or apron. There are thus some intersections of highways and aprons, where only ATTs should come during normal operations, the locations of these intersections are visualised in Figure 1. As there are only autonomous vehicles interacting with these ATT-only intersections, specialised intersection management strategies can be used to regulate the flows of ATTs at these intersections. Figure 2 gives an overview of which routes the ATTs utilise at the intersection, as well as how the layout of the ATT-only intersection looks like.

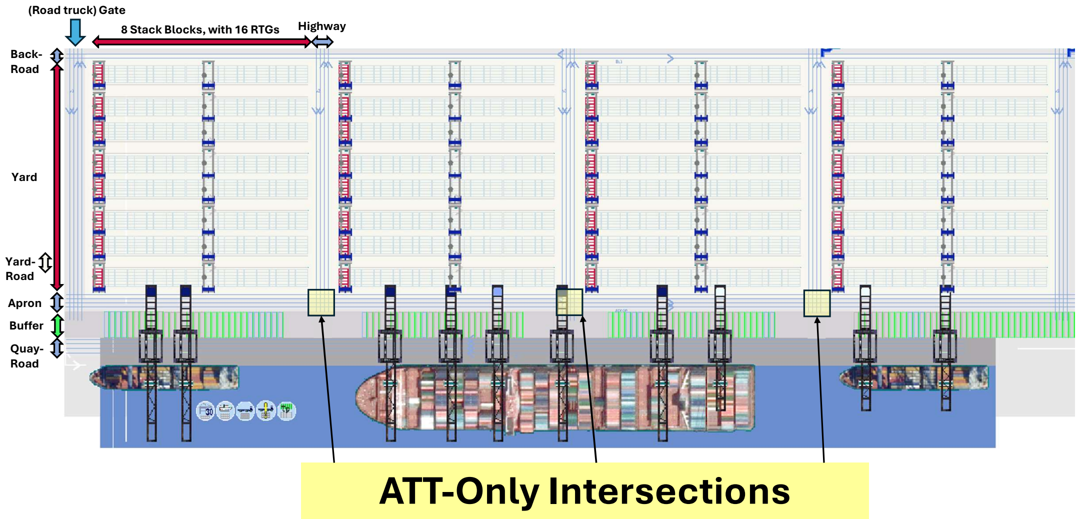

Figure 1: Locations of ATT-only intersections and other elements of the terminal

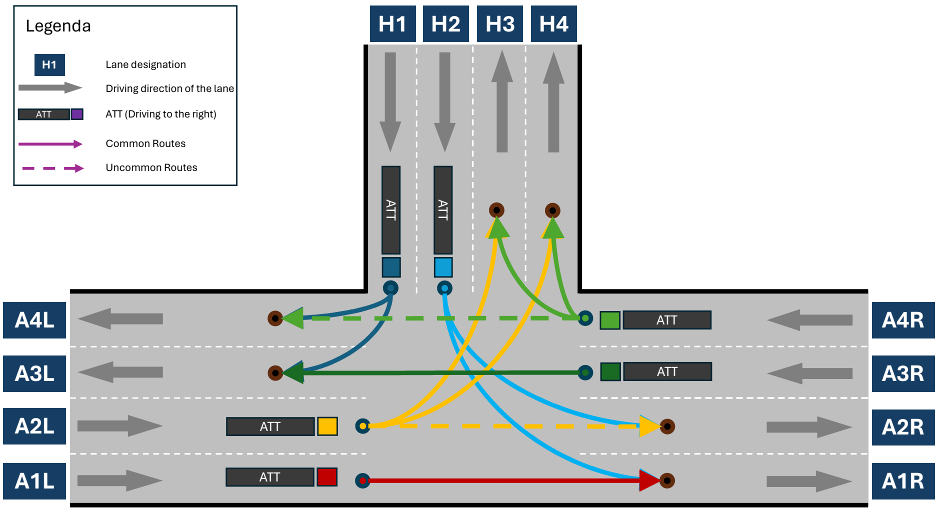

Figure 2: Layout and routes of an ATT-only intersection

There have not been many studies on the subject of ATTs, mainly because they are still a recent development. The few available studies have focused either on general ATT efficiency or traffic rules for mixed traffic intersections. There is thus a research gap on how the intersection strategies of ATT-only intersections can influence the productivity of a container terminal. This leads to the main research question:

”How does the intersection strategy of autonomous terminal tractor-only intersections influence the productivity of an RTG-based terminal?”

The main method with which this question is answered in this thesis, is through the design of an ATT model, an ATT-controller model and an intersection management system (IMS) model, with which simulation experiments have been performed featuring different intersection strategies. Here the ATT model is the whole model of the vehicle which is able to operate on the terminal model. The ATT controller model is built into the ATT model, and is the main decision making module of each individual ATT. The IMS model coordinates the ATTs at ATT-only intersections.
These three models have been built into the TIMESQUARE terminal simulation environment of Portwise, to simulate the operations of ATTs within an RTG-based terminal. Preliminary to the design of these models, a system analysis of the RTG-based terminal and the ATT itself have been conducted, as well as a literature research on the simulation of ATTs/AVs and ATT/(C)AV/AGV intersection strategies.

For the model of the ATT, input data has been given by an ATT developer. There are (at the time of writing) also 11 other ATT developers publicly active in various phases from prototype testing to the first full fleet operations at container terminals. All developers claim near full autonomous operations with their ATTs, with the possibility for tele-operations for problematic situations. All of them also use a similar sensor set on their ATT to perceive their surroundings and other vehicles around them. This sensor set nearly always consist out of at least a LiDAR, Camera and Radar. Dependant on the design philosophy of the ATT-developer, either a multi-layer decentralised or multi-layer distributed control structure could be used. ATT developers have stated that they use a multi-layer decentralised control structure for their ATT fleets, so for this thesis, this structure is also assumed.

In order to function as an ATT would in real-life, the ATT model needed to include the following features: a vehicle detection system akin to the sensors on the ATT, and a rule-based actuation system which translates inputs from sensors and IMS into actions for the ATT. These features have been implemented into the model of the ATT controller, which in its turn has been included in the model of the ATT. The controller model includes the main decision making logic, which uses the perception of the ATT, the overlap of its path with other vehicles and their paths, and the location of the ATT in relation the infrastructure, to determine its decisions with regard to actuation. This is coordinated by three sets of rules within the ATT controller model: the path conflict-, buffer interaction- and yard interaction rules. All major equations used by the controller logic have been derived from the mathematically proven collision-free minimum safety distance equation of Shalev-Shwartz, Shammah, and Shashua, 2017.

In order to coordinate traffic at the ATT-only intersections, the model of the IMS has been developed. This system coordinates the access of the ATTs to the ATT-only intersections. It does this by utilising an entry-and exit check to determine if an ATT can enter the intersection without being hindered and cross the intersection without stopping. Dependant on the intersection strategy, it also utilises a matrix-check using a conflict matrix, to determine if multiple vehicles can safely enter the intersection together. There have been four intersection strategies included in the IMS:

- **One-Vehicle-at-a-Time, First-Eligible-First-Serve (One-FEFS)**: Gives access to the next vehicle in queue at the intersection that can enter the intersection without being hindered and cross the intersection without stopping, with a limit of one vehicle at a time on the intersection.
- **Multiple-Vehicles-at-a-Time, First-Eligible-First-Serve (Multi-FEFS)**: Gives access to the next vehicle in queue at the intersection that can enter the intersection without being hindered and cross the intersection without stopping, and which does not conflict with vehicles which are already on the intersection, with no limit on the amount of vehicles on the intersection.
- **QC Destination Priority (QC-Prio)**: Same as Multi-FEFS, but registers vehicles which have a QC as their destination in front of vehicles that do not, in the queue.
- **Priority for Delayed ATTs with QC Destination (Delay-Prio)**: Same as QC-Prio, but now queue position among vehicles which have a QC as their destination is determined dependant on the elapsed time from the ATT getting their order. With ATTs with a higher elapsed time (delay) than other vehicles, getting queue priority over those other vehicles.

In terms of KPIs, QC productivity which is measured in containers handled per hour per QC, is used in the experiments as the main KPI to measure the overall terminal productivity with, as this is an industry standard. Intersection throughput and percentage of ATT drive status standing still queuing, are two other used KPIs in this study.

Simulation experiments have been conducted using the intersection strategies and various ATT fleet sizes, for both peak-load and off-peak-load scenarios. Here is was found that for the peak load scenario, switching from a one-vehicle-at-a-time intersection strategy type to a multiple-vehicles-at-a-time one, will generally increase the QC productivity and intersection throughput with a significant margin ranging from 1 to 1.9 containers per hour (increase of 5% to 8%). Next, it was found that utilising either the Multi-FEFS or the QC-Prio intersection strategy has lead to the best performances in terms of terminal productivity, with the former performing better at the higher ATT fleet sizes and the latter performing better at smaller ATT sizes. There were no statistically significant differences found between the results of the two strategies. The Delay-Prio strategy did not perform best in any test. In essence, has the difference between the tested intersection strategies limited consistent impact on the QC productivity, as long as multiple vehicles are allowed on the intersection at once.

The experiments with the off-peak scenario showed that there is nearly no influence of the intersection strategies on the terminal productivity during these kinds of operations. As such, there is not really one strategy outperforming all others in this scenario, however the QC-Prio strategy did perform the most consistently well across the fleet sizes in this scenario, with an average QC productivity increase of 0.5 containers per hour (2% increase) over the One-FEFS strategy. When comparing the results of the peak and off-peak scenarios, it was found that the off-peak scenario vastly outperformed the peak scenario in terms of containers handled per QC, with an approximate gap ranging from 5 to 8 containers per hour (24% to 31% increase), increasing with the fleet size. This indicates that congestion of the terminal road network during peak operations is a significantly hampering the performance of the ATT model, as the ratio of ATTs per QC is the same across the peak and off-peak scenario.

Every configuration of the ATT model had a very significantly lower QC productivity than the benchmark TT model.Here the gap in QC performance of the off-peak-load scenario was smaller than of the peak-load one, with an average approximate gap of 6 containers per hour for the off-peak-load scenario and 9 containers per hour for the peak-load scenario. Which means that going from the ATT model to the TT model will constitute an average increase of 28% in the off-peak-load scenario and an average increase of 42% in the peak-load scenario.

From some additional experiments it was found that:

- An increase in the maximum speed limit for the ATTs corresponds with a small increase in QC productivity.
- The perception time-step has an inconsistent but significant impact on the performance of the ATT model and the QC productivity, with the slower time-step of 0.1 seconds mostly performing better than the time-step of 1 second.
- A higher road truck arrival rate has a significant negative impact on the QC productivity and intersection throughput.
- The test configuration with the conflict matrix without trailer sway had a noticeably lower QC productivity and intersection throughput as the one with a conflict matrix which included trailer sway, which is an illogical outcome, but no real explanation has been found for this.

The largest limitation of the ATT model, is that the ATTs are bound to the route and path they are given at the time of accepting their job, and they can never deviate from that given route or path. This leads to unnecessary congestion on lanes, where there is room for potential overtakes in the lane next to it. This absence of a dynamic routing component also hampers the validity of the ATT model, as ATT developers expect their vehicles to have this feature in real life operations. Though it is not clear if the current ATT developments already have this feature fully included, ATTs in real-life do already have to option for human tele-operation, which makes it possible to manually alleviate congested situations. It is due to these reasons that there are more traffic jams in the model than will be expected to happen in real life, and as such are the performance values from the ATT model results not yet indicative for the potential real-life ATT performance.

For further research on ATT simulation models, it is recommended to:

- Include dynamic routing in the ATT model, so ATTs can change their route to a more optimal one, dependant on congestion of the terminal road network.
- Include dynamic pathfinding in the ATT model, so ATTs have the possibility to change to a different lane when they detect congestion on their current lane, and overtake slow moving or stationary vehicles.
- Add a more realistic road truck model, as to be able to experiment with the ATT model in a more realistic mixed-traffic environment.
- Test with and develop other intersection strategies, as there are possibly more efficient ones which have not been featured in this thesis.
- Optimise the model for simulation speed, as to prevent excessive simulation run times for large fleets.
- Develop strategies to ease congestion, as this has been observed to be a significant contributor to inefficiencies within the ATT-model.
- Develop a model using real-life ATT operations, when data is available of such an example operation featuring a large ATT fleet somewhere.
- Perform tests with varied road layouts, as only one layout has been tested in this thesis, and improvements in productivity could be possible with differing layouts.

Contents

Abbreviations

Abbreviation	Definition
(A)TT	(Autonomous) Terminal Tractor
(C)AV	(Connected) Autonomous Vehicle
CT	Container Terminal
FCFS	First Come First Serve
FEFS	First Eligible First Serve
HDT/HDV	Human Driven Truck/Vehicle
IMS	Intersection Management System
LiDAR	Light Detection And Ranging
MPC	Model Predictive Control
Multi-FEFS	Multiple-Vehicles-at-a-Time First Eligible First Serve
One-FEFS	One-Vehicle-at-a-Time First Eligible First Serve
OEM	Original Equipment Manufacturer
P/D (lane)	Pick-up/Drop-off (lane)
QC	Quay Crane
RTG	Rubber Tired Gantry
TOS	Terminal Operating System

1
Introduction

1.1. Introduction to the Context

Within the world of container terminals, Automated Guided Vehicles or AGVs have since 1990 been the go-to solution for automating horizontal container movements on large newly built container terminals. These so-called greenfield terminals typically feature a perpendicular layout when utilising AGVs, which separates the zone where the AGVs drive from the zone where the human driven road trucks drive.

There is however also an other type of container terminal layout, the parallel layout which was the standard layout from the time before AGVs existed and is still widely used in terminals around the world today. A visualisation of both a perpendicular and a parallel layout can be seen in Figure 1.1. In these parallel layout terminals, road trucks and terminal tractors (TTs) utilise the same road network to deliver and pick-up containers. AGVs as they are, can not be implemented to drive on these parallel layout terminals for safety reasons. AGVs were designed to drive in a closed off area where they do not have any interaction with human driven vehicles (HDVs) and as such, they were not designed to feature the sensors and control structures necessary for mixed traffic use.

AGVs require a significantly larger CAPEX to implement than TTs. This is because of a few factors: AGVs have a higher load per axle than TTs, which increases needed degree of reinforcement of the quay and pavement of the terminal, and AGVs are as equipment also more expensive to buy than TTs. There are also a lot of existing terminals with a parallel layout and RTGs as yard equipment, which want to replace their human driven TT fleet with an autonomous alternative, without having to overhaul their infrastructure (Gijsbert Bast [Portwise] personal communications, 2023, September - October). To fill the need for a cheaper autonomous horizontal transport solution which can be implemented into existing container terminals with a parallel layout, autonomous terminal tractors (ATTs) are currently being developed. ATTs have mostly the same characteristics a TTs, with the distinction that they do not require a human on board of the vehicle for operations. The largest stand-out feature of an ATT, is that it could theoretically operate within an existing brownfield terminal without the need of changing the infrastructure on the terminal, while interacting with HDVs in mixed-traffic. ATTs do have sensors with which they can detect other vehicles and objects on the road, and they should be able to make independent decisions based on these sensor inputs (AI-Drivers, 2023).

ATT developers are currently at the point of conducting single vehicle and small fleet tests in mixed traffic. There are however, still a lot of unknowns regarding the efficient implementation of a full fleet of ATTs into a terminal. This thesis aims to tackle one of those unknowns, namely the coordination and strategy of ATT-only intersections.

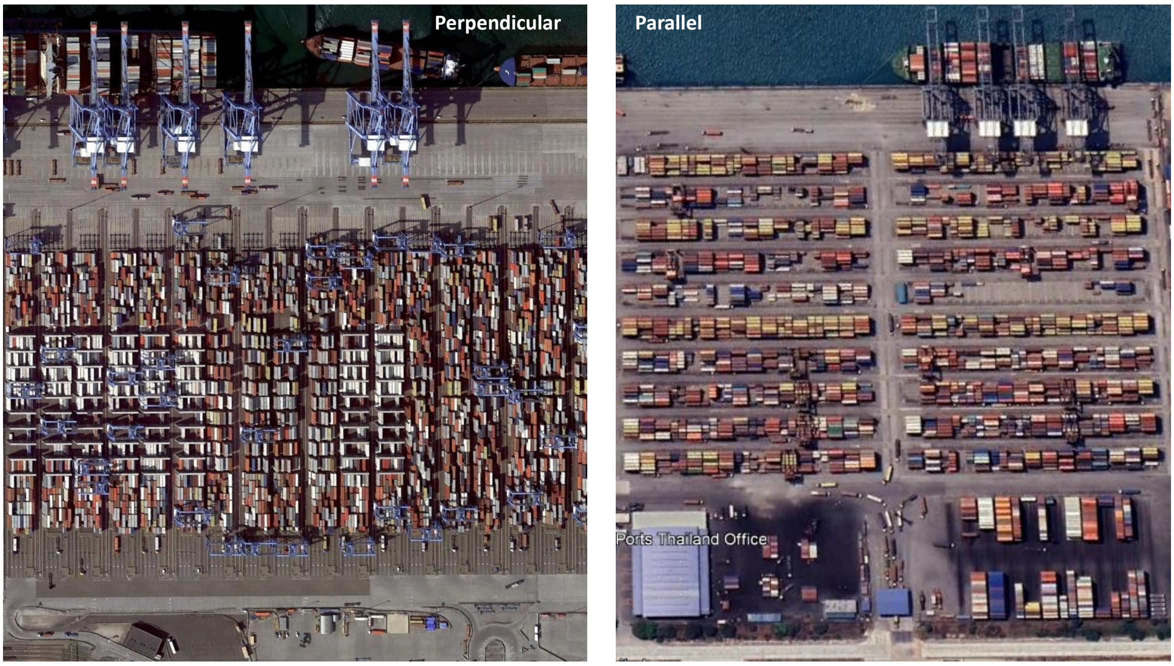

Figure 1.1: A terminal with a perpendicular layout (left) and a terminal with a parallel layout (right)

1.2. Introduction to the Case Study

The case study for this thesis will be performed at Portwise, which has commissioned this study on an ATT simulation model. Portwise is a logistics consultancy and simulation company, specialised in port, terminals and warehousing. They have created their own container terminal simulation software called TIMESQUARE, which runs on eM-plant/Siemens Plant Simulation. Having a working model of an ATT is becoming quite important to them, as ATT developers have started to enter the testing and implementation phases for their solutions, while terminal operators are starting to ask Portwise to include simulations with ATTs.

Even though Portwise is the commissioner, they are not the problem owner. Terminal operators of non-automated terminals are at the base of this problem, as they want to start with integrating autonomous vehicles into their terminals, but see that there is not a lot of knowledge publicly available on integrating ATTs into a human operated terminal, especially in terms of fleet, routing and intersection strategies, and their influence on terminal productivity. Terminal operators have an interest in knowing how these ATTs could best be integrated within an RTG-based terminal, in order to maximise the effectiveness of the horizontal transport of containers within their terminal.

Here ATT developers are a stakeholder from the other side, as they want to start to sell their ATTs to terminal operators, but experience difficulties with this as ATTs are not yet a proven technology. They currently have a clear vision and test results of how their ATTs function as stand alone vehicles, but have less knowledge about how their ATTs would function in a large fleet during terminal operations.

The aim of the case study is to provide Portwise with a working ATT model for further use in their simulations. The academic aim of the study is to utilise the built model to research the impact which certain ATT-only intersection strategies have on the productivity of the terminal in which they are implemented.

1.3. Current Literature

The literature tackling specifically ATTs or autonomous vehicles (AVs) in RTG-based terminals in general is quite limited, as ATTs are still a relatively recent development (Gerrits, Mes, and Schuur, 2020). At the moment of writing, there are a handful of studies on these topics.

Gerrits and Schuur, 2022 and Gerrits et al., 2019 explain the basics of how one could implement these ATTs with regards to intelligent decision making from the vehicle, and how these vehicles could theoretically interact with HDVs and equipment on the terminal.

Gerrits, Mes, and Schuur, 2020 went further in depth by simulating ATTs in a basic rendition of an RTG-based terminal using the discrete-event simulation tool Siemens Plant Simulation. Here ATTs interacted with simulated human controlled road trucks, RTGs and quay cranes. The field-of-view of the ATT has been modeled as one single 180 degree front facing LiDAR, with the ATT being able to detect other vehicles with it and brake when it would otherwise collide with a vehicle. The study however does not mention the effective range of the vehicle detecting sensor. The study experimented with the number of deployed ATTs in the terminal as a variable, and looked at how this impacts various performance indicators in the terminal. The layout of the tested on terminal itself did not feature any intersections.

Horst, 2019 has developed a traffic control system for ATTs engaging in ATT-HDV mixed intersections (as a BSc thesis under the supervision of Gerrits and Mes). The traffic control consisted out of a set of possible leading rules of which vehicle would receive priority at intersection or conflicts. The system was tested using the same discrete-event simulation tool as Gerrits, Mes, and Schuur, 2020 and minimizing the total number of vehicles queuing at an intersection was observed to be the most efficient traffic rule.

Hong et al., 2023 have developed an optimisation model for ATT scheduling while interacting with loading and unloading equipment. The model made use of Genetic and Enumerated Algorithm to come to an optimised solution. However, in this study 100% ATT integration was assumed and also interactions with road trucks were omitted.

Ng, Ong, and Zhou, 2022 looked at the efficiency of different turning policies at junctions in mixed traffic container terminals, for various ATT penetration rates and traffic densities. This was also for ATT-HDV intersections, and one of the test configurations consisted out of ATT only lanes. The experiments were conducted using the microscopic traffic simulation tool PTV Vissim.

Chen, Xu, and Wang, 2023 have built a mathematical model of ATTs and road trucks interacting in mixed traffic container terminals, with rule-sets giving either the ATTs or road trucks priority on the other. The model was solved using a Genetic Algorithm and experiments were conducted using a varying number of road trucks while keeping the number of ATTs the same.

The found literature thus focuses mainly on the conflict situations between ATTs and road trucks at intersections.

1.3.1. Research gap

From the set of studies published on ATTs in an RTG-based terminal, three of them used microscopic simulation as a research method (Gerrits, Mes, and Schuur, 2020), (Horst, 2019) and (Ng, Ong, and Zhou, 2022). These simulation studies, were mainly focused on the optimization and performance side of ATTs. In all three, there were traffic rules for mixed ATT-road truck intersections included in the experimental setup, but no further interactions between ATTs and road trucks were explored. Chen, Xu, and Wang, 2023 has researched interaction rules between ATTs and road trucks, with respect to truck scheduling, but has only tested this using a mathematical model and genetic algorithm.

The research on ATTs in an RTG-based terminal is thus limited to their interactions at mixed ATT-road truck intersections and their general performance in simulations. There presently are no studies centered around intersection strategies for ATT only intersections. In an RTG-based terminal, there are still traffic heavy areas on the seaside of the terminal, where only ATTs are allowed to drive. At this moment, there is no research into how these intersections could be controlled in the most efficient manner, and neither is it known if different intersection strategies on these ATT-only intersections actually have any influence on the overall pterminal performance.

There is thus a research gap on how intersection strategies for ATT-only intersections could influence the productivity of the RTG-based terminal which they are implemented in.

1.4. Research Question

The aforementioned research gap can be filled by designing a vehicle and intersection controller for ATTs in an RTG-based terminal, experimenting with differing intersection strategies and measuring their impact on the terminal productivity. This has been formulated in the following research question:

"How does the intersection strategy of autonomous terminal tractor-only intersections influence the productivity of an RTG-based terminal?"

1.4.1. Sub-questions

Answering the following sub-questions will help to answer the stated research question:

1. How does an RTG-based terminal system function, which operational processes are present on it and how can the operational performance of it be measured?
2. How does the internal system and control structure of an ATT function, and how does the ATT interact with other vehicles?
3. What is currently known in the literature about simulating ATTs/AVs and ATT/(C)AV/AGV intersection strategies?
4. How can the controller of an ATT be modelled in a microscopic discrete event simulation to be a valid representation of ATTs in real-life?
5. How do different intersection strategies impact the operational performance of the ATT model, and how do the ATT performances compare to a model of a human controlled TT?

1.5. Scope

The scope of this thesis is limited to designing and testing an ATT model, ATT-controller model and intersection management system (IMS) model within an existing discrete event simulation model of an RTG-based container terminal, as well as performing the necessary system analysis and literature research for this. The validation of the ATT model will be partially done by EasyMile, which is an ATT developer, partially by experts from Portwise and partially by the author himself. The simulation model of the terminal itself has been created and validated by Portwise.

1.6. Methodology and Thesis Outline

In this section, the research methods are discussed with which the aforementioned sub-questions will be answered, and the outline of where these methods are located within the thesis is given.

Sub-question 1, *How does an RTG-based terminal system function, which operational processes are present on it and how can the operational performance of it be measured?*, will be answered by conducting a system analysis of an RTG-based terminal. This should give insight into which processes are present on the terminal, at which points in these processes vehicle interactions happen and how the operational performance of the terminal could be measured. This is discussed in Chapter 2.

Sub-question 2, *How does the internal system and control structure of an ATT function, and how does the ATT interact with other vehicles?*, will be answered by performing a system analysis of an ATT, as well as by analysing the interactions the ATT has with other vehicles on the terminal. This should give a clear understanding of how ATTs operate in a terminal environment, onto which the model on the ATT can be based. This is discussed in Chapter 3.

Sub-question 3, *What is currently known in the literature about simulating ATTs/AVs and ATT/(C)AV/AGV intersection strategies?*, will be answered by conducting a literature review on these topics. This is discussed in Chapter 4.

Sub-question 4, *How can the controller of an ATT be modelled in a microscopic discrete event simulation to be a valid representation of ATTs in real-life?*, will be answered through the design, modeling and validation of a controller of an ATT. The simulation model will be made using TIMESQUARE and configured using data from an ATT developer. The validation of the model will be done partially by EasyMile, partially by Portwise and partially by the author. This will be discussed in Chapter 5.

Sub-question 5, *How do the different intersection strategies impact the operational performance of the ATT model, and how do the ATT performances compare to a model of a human controlled TT?*, will be answered by conducting experiments with the ATT models with differing intersection strategies and the existing model of a human controlled TT. The experimental plan for this will be discussed in Chapter 6 and the results of the experiments will be discussed in Chapter 7.

After all sub-questions are answered, a conclusion can be drawn to the research question in Chapter 8.

Lastly, recommendations for further research are stated in Chapter 9.

2 Container Terminal as a System

In this chapter, the RTG-based container terminal is analysed from a systems engineering point of view. First, the infrastructure and layout of an RTG-based terminal is analysed. Then an overview is given of all vehicles that operate within the terminal, and all relevant operations which are conducted within the terminal are analysed. Lastly, the operational performance measurements typically used for container terminals are analysed. By conducting these analyses, an answer can be formulated to sub-question 1: *How does an RTG-based terminal system function, which operational processes are present on it and how can the operational performance of it be measured?*

Container terminals are pieces of logistical infrastructure which facilitates the movement of containers between two modes of transport, and storage of containers for a short amount of time. These terminals exist in a plethora of different forms and configurations, and as such it is important to specify which kind this study will focus on. The analysis provided in this chapter is based on information from Notteboom, Pallis, and Rodrigue, 2021, Gupta et al., 2017 as well as the Port Academy program of Portwise and Konecranes.

The terminal of interest is one which has the ability to move containers between vessels and road trucks, all other possible modes of transport are left out of scope. It is also fully human operated except for the ATTs and the terminal makes use of a parallel layout. In this parallel layout terminal, the containers in the yard stacks will be serviced by RTGs and horizontally transported within the terminal by (A)TTs. The road network on the terminal will be utilised by both (A)TTs and road trucks. A schematic overview of this type of terminal is visualised in Figure 2.1.

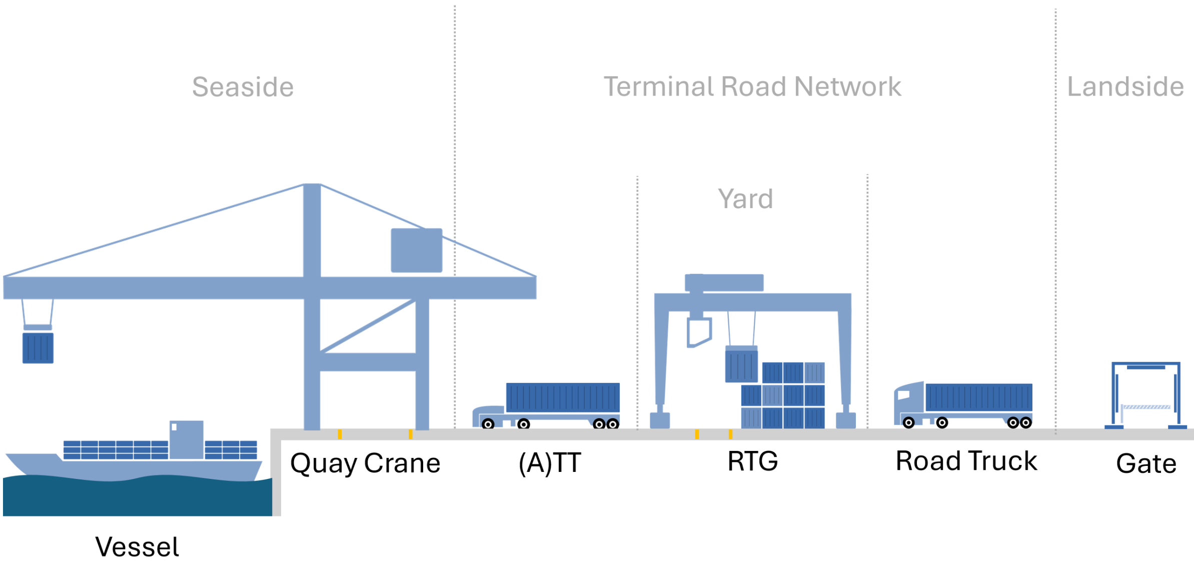

Figure 2.1: Schematic of a container terminal with parallel layout and RTGs

At the highest abstraction level, the container terminal of interest can be seen as a system where containers are brought in by either vessel or road truck as input and where containers also leave by road truck or vessel as output. It has certain characteristics or requirements like the types of equipment used, the terminal layout and the terminal road network layout. These are the most basic principles which dictate the performance of the terminal. This performance can be measured by many different KPIs, though the three most utilised are QC productivity, container throughput and road truck dwell time. This all is visualised in a black box diagram in Figure 2.2.

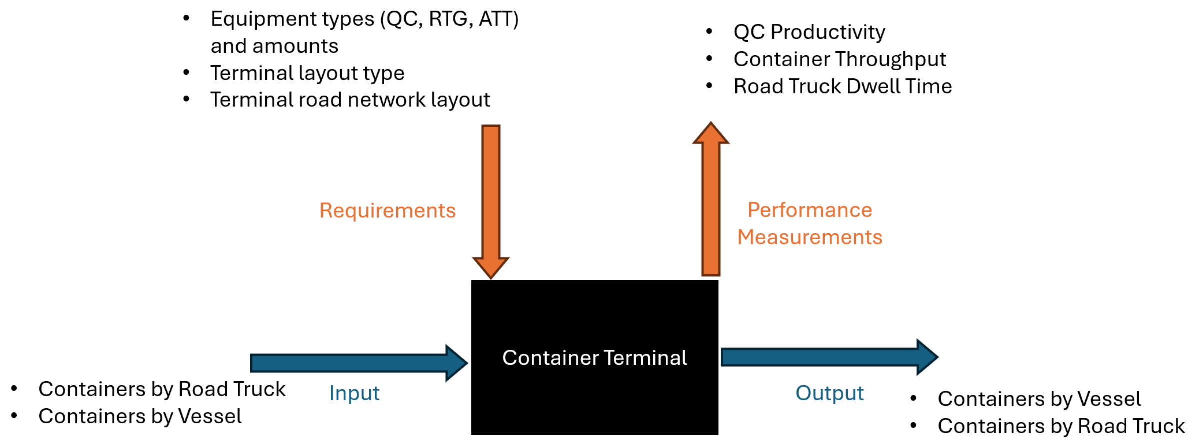

Figure 2.2: Black Box Diagram of a container terminal

2.1. Terminal Infrastructure

All non-moving parts of the terminal are to be considered its infrastructure. The terminal can be divided into four parts in which infrastructure is located: seaside, yard, landside and road network. These parts are visualised in Figure 2.3.

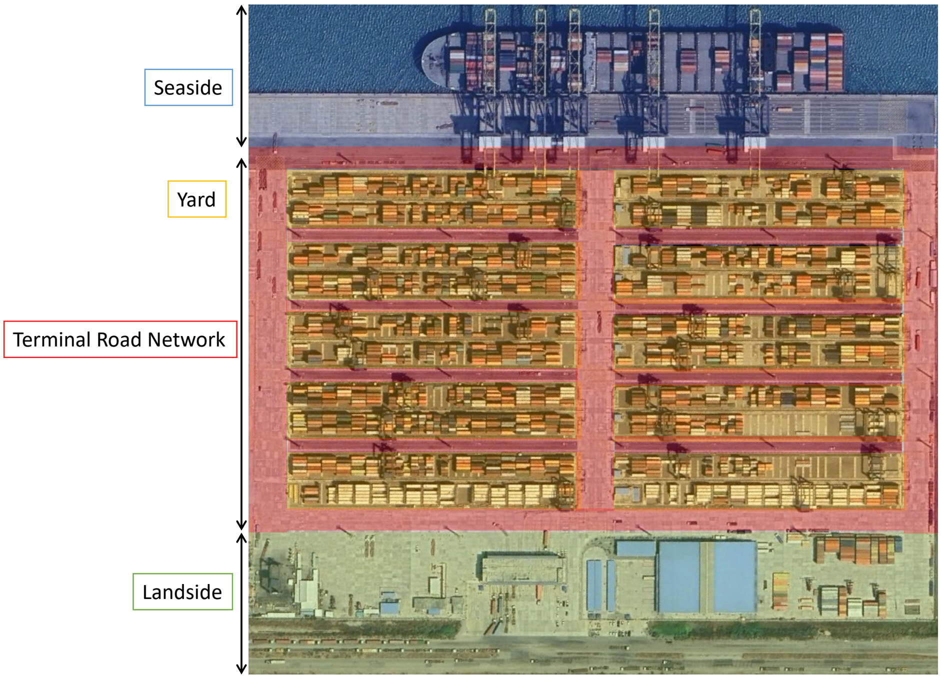

Figure 2.3: Parallel structured container terminal (HCT Laem Chabang Terminal D), with section overlay

2.1.1. Seaside

The seaside of a terminal is indicative of the quay, and berthing spots for (feeder) vessels and barges. There are a lot of different quay forms and layouts possible, with most of them mainly being dependant on the available land area. For this study, the assumed quay has a basic linear layout like visualised in Figure 2.3.

On the quay there are ship-to-shore quay cranes which load and unload containers to and from the berthed vessel. Under the quay cranes there are typically 4 to 6 lanes for (A)TTs to drive on, in order to deliver or pick-up containers at designated spots under a crane. Next tot these quay lanes lay the rails on which the quay cranes ride. Between the quay lanes and the apron, there is an area designated for the waiting/buffering of ATTs, here they have to wait if it is not yet their turn to pick-up/drop-off their container under the QC. It is important to note that these buffer areas are only needed in terminals with autonomous or automated horizontal transport vehicles. Human driven TTs typically wait wherever they find space, and are not bound to a specific waiting area. The buffer area is also used to store the hatch covers of the vessel during loading/unloading, these are stored behind the QC, and as such are the buffer spaces behind a QC not available for ATTs. When ATTs are moving between the waiting/buffer area and quay lanes, they have to cross the quay crane rail. A diagram of the seaside and the road network connected to the seaside is visualised in Figure 2.4.

The apron serves as a connection between the buffers on the seaside and the rest of the terminal road network. The (A)TTs can move freely between the apron, waiting/buffer area and the quay lanes, as long as the path they want to travel on is free and they are given clearance for their move by the Terminal Operating System.

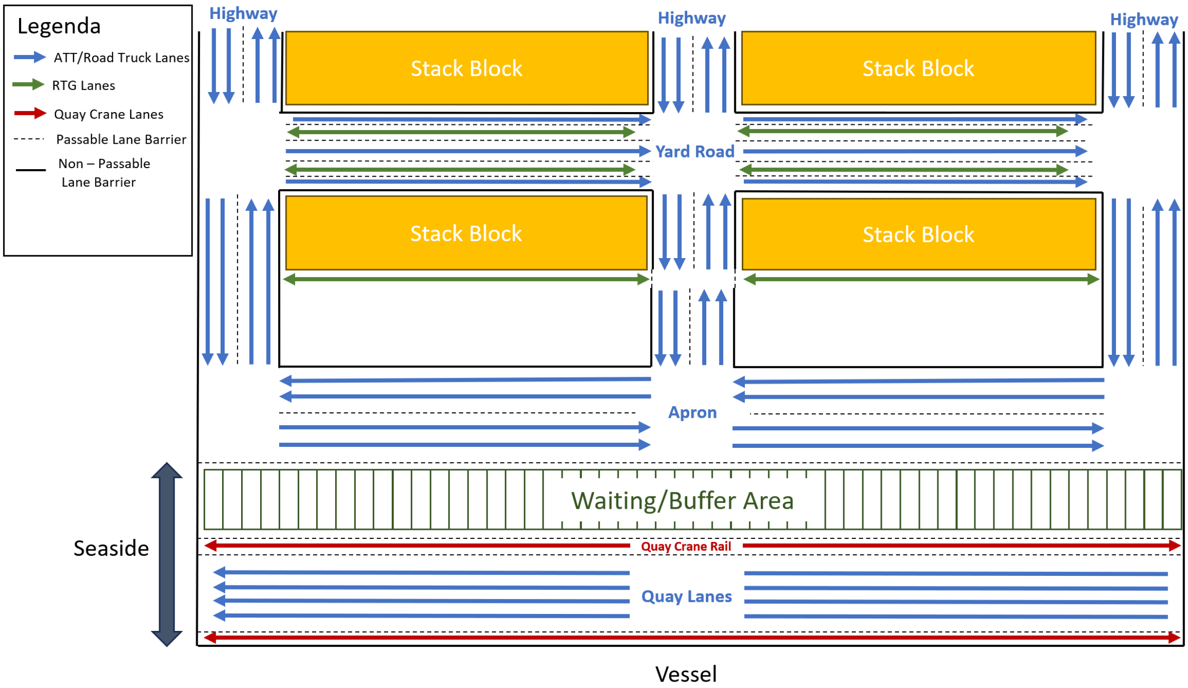

Figure 2.4: Diagram of the road network on the seaside

2.1.2. Yard

Between the sea- and landside, there is a designated area for container storage, this area is called the yard. Both incoming and outgoing containers will first pass through the yard, as a direct transshipment between two modes is not practically possible. As such, the yard acts as a gathering and sorting place for these containers between modes of transport.

The yard is divided into stack blocks, each yellow rectangle in Figure 2.3 and Figure 2.4 is a separate stack block. Containers are placed in a specific place within the stack block by defining a bay (x-axis), row (y-axis) and pile (z-axis) number. Stack blocks have a certain limit of the amount of containers in each axis. For yards using RTGs, these limits are typically 6 to 8 containers in bay width, 30 TEU in row length and 4 to 6 in pile height. Terminal layouts are defined by the orientation of the stack blocks to the quay wall. In this study a parallel layout is assumed, this means that the stack blocks are placed parallel to the quay wall.

Regular containers need little more than a place to stay in the yard. There are however two types of containers which require special handling, these are reefer containers and empty containers. Both of them have special designated spaces within the yard where they are placed. Reefer containers have an internal cooling system and are usually used to ship perishable foods. As such they need to be connected to a power outlet while they are stored in the yard, this is done in so called reefer stacks. There are specialised reefer mechanics on site to plug and unplug these containers. Empty containers have different pile height requirements and can be handled by a special empty handler.

2.1.3. Landside

The landside of the terminal is comprised of the gate where road trucks enter and leave the terminal, and other services like rail terminals, container repair, equipment maintenance, administration and container freight station. These latter services will be left out of scope for this study, so the only part of the landside to be considered is the gate.

At the gate, road trucks and their inbound containers are registered and occasionally also checked by customs. The road truck is then given an instruction to which yard bay it has to drive in order to unload and/or load its container. When exiting the terminal trough the gate, the road truck will undergo a similar process as when it entered.

2.1.4. Terminal Road Network

The different elements on the terminal are connected using a simple network of roads. These roads consist out of: ”highways” which run perpendicular through the whole terminal, yard roads which run parallel to the stack blocks, the ”apron” which runs parallel to the quay road and the back-road which runs parallel to the stack block at the land side.
Quay roads could technically also be considered part of the road network, but for this thesis they are already classified under the seaside part.

Highways typically consist out of multiple one-way lanes in a bi-directional configuration. Yard roads also have multiple one-way lanes, but typically utilise a one-directional configuration. In yard roads, the lanes closest to the stack block are designated as a pick-up/drop-off (P/D) lane where road trucks and (A)TTs will stand and queue to be handled by the RTG. The lane in the middle is designated as a bypass lane for the P/D lane, this way vehicles can pass parked trucks when they need to be somewhere further on in the row. In between the P/D lane and the bypass lane, is a lane designated for the wheels of one side of the RTG to drive on, the lane for the wheels of the other side of the RTG runs in between the stack blocks, and both of these RTG lanes also cross the highways.

The apron is used as a connection road between the buffers on the seaside and the highways leading to the yard roads. Highways intersect with yard roads at the end of every stack block. On these intersections, the road trucks and (A)TTs will have to make a turn if they have to change between the two road types. There are usually no traffic lights installed at these intersections, so drivers need to actively look in order to determine if it is safe to take the turn or pass the RTG lane. There are also specific traffic rules in each terminal, these determine for example: who has right of way, what the maximum speed is and where parking is allowed (Hutchison-Ports, 2023).

An example of a terminal road network featuring one yard road, three highways, one apron and one back-road with gate connection, is visualised in Figure 2.5

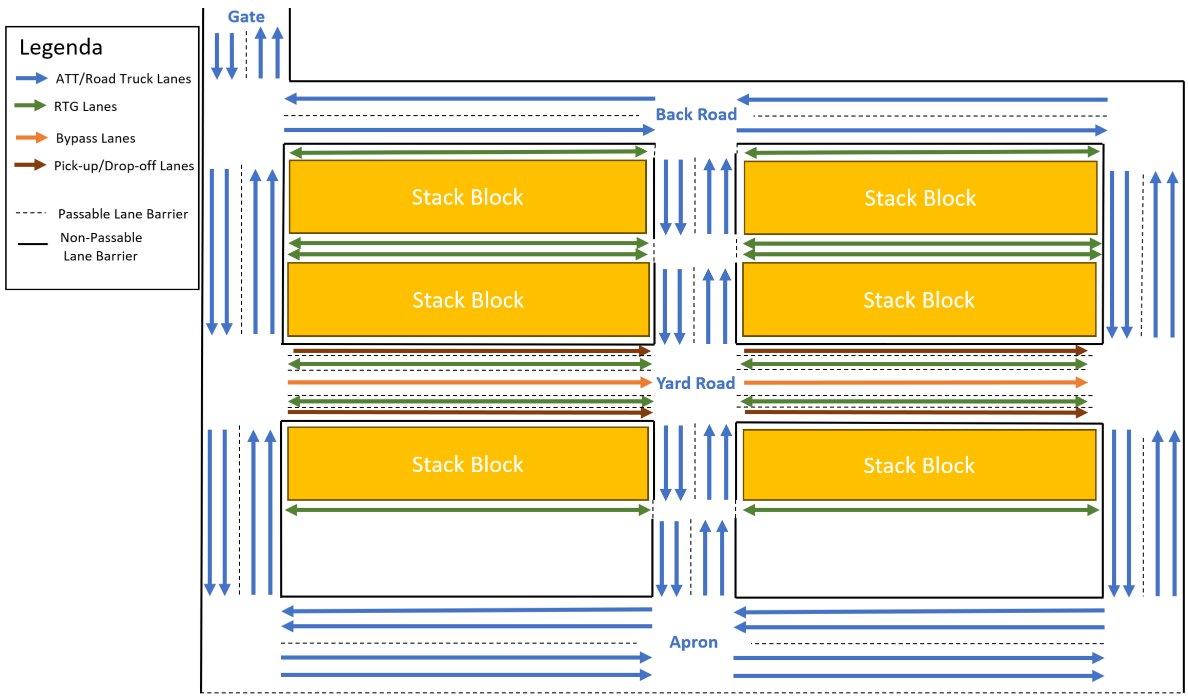

Figure 2.5: Diagram of a terminal road network

A more in depth explanation about the different intersections within the terminal road network, is given in Section 3.8 for HDV-ATT intersections and Section 3.7 for ATT-only intersections.

2.2. Vehicles on Terminal

With the infrastructure of the terminal defined, it is now possible to define all vehicles which are active on the terminal, and utilise said infrastructure. Vehicles include all machines in the terminal which are capable of moving themselves. The following vehicles are just the ones included in the terminal type of interest, all other possible terminal vehicles are left out of scope. In Table 2.1 all vehicles are listed which are present within the analysed terminal type.

Vehicle	Main Use	Area of Operation
ATT	Horizontal transport of containers within the terminal	Yard roads, Highways, Back-road, Apron and Quay road
RTG	Loading/unloading containers from/to the yard to/from a horizontal transport vehicle	Yard roads and occasionally Highways
QC	Loading/unloading containers from/to a vessel to/from a horizontal transport vehicle	Quay
Road Truck	Horizontal transport of containers from/to the terminal to/from the outside world, via road	Yard roads, Highways, Back-road and Gate

Table 2.1: All vehicles which are present on the terminal during normal operations

2.2.1. General Horizontal Transport

Horizontal transport in a container terminal, refers to the transport of containers between the QC and the yard. In a traditional RTG-based container terminal with parallel layout, TTs are always used to facilitate the horizontal transport of containers within the terminal. In other types of terminals, other forms of internal horizontal transport vehicles could be used, which include AGVs and straddle carriers, but both of these require different yard layouts to function effectively, so they are excluded from the scope of the analysis.

ATTs are developed to function in the same operational conditions as TTs are, and in terms of operations they are mainly similar. Although it should be possible for TTs and ATTs to coexist within the same terminal system, it makes the system more complex. The general end goal of both terminal operators and ATT developers is that ATTs can completely take over all tasks of TTs within an RTG-based terminal. As such, human driven TTs are also excluded from the scope of this analysis, and all internal horizontal transport of containers within the terminal will be solely facilitated by ATTs.

The horizontal transport of containers which are imported to or exported from the terminal via the gate and outside road, is always done by road trucks.

2.2.2. Autonomous Terminal Tractor (ATT)

The autonomous terminal tractor is a driver-less horizontal transport machine mainly used for moving containers between the yard and the quay. They can also be utilised during so called ”housekeeping” operations, where a container needs to be transported between two different bays within the yard.

The ATT is the autonomous version of the widely used TT, which still requires a driver to be on board to control the vehicle. ATTs instead utilise a set of sensors for their perception and an onboard decision making system for their driving decisions. All current ATT developments do however still have (remote) human oversight and a tele-operator ready to take control over the vehicle when it encounters unexpected situations. ATTs are also still a largely recent development, with only a very limited amount of ATTs in some sort of operation. Most ATT developments are still in testing or prototyping phase, a summary of the current ATT developments can be found in Section 3.2.

The ATT is part of a tractor-trailer system, where the ATT pulls a trailer onto which containers can be loaded. These trailers have room for one 40ft container or two 20ft containers, and are attached to the ATT using a kingpin system. If the trailer is fitted with air-brakes, then the controls for these are also connected to the ATT via cables. Dependant on the ATT developer, there might also be sensors on the trailer itself, so the ATT can also look directly behind itself.

As ATTs are the centrepiece of this study, they have their own chapter in which they are explored much further in depth, namely Chapter 3.

2.2.3. Rubber Tired Gantry (RTG)

Rubber tired gantry cranes are typically used in terminals with a parallel yard layout to pick and place containers in the yard, and to move them between the yard and horizontal transport vehicles. They are characterised by the rubber tired wheels on which they drive around. These wheels can turn 90 degrees on special turning pads, which gives them the flexibility to move both parallel and perpendicular within the yard. This means that RTGs are not bound to a specific block or row within the yard, but can be deployed wherever in the yard that they are needed the most. However, when they are moving between blocks, they utilise and cross the same roads as which the (A)TTs and road trucks are driving on, and as they are relatively slow moving vehicles, they might cause hindrance to the flow of the road network.

For grabbing onto containers, RTGs use a spreader which locks onto the top of the container, using the same holes as a twist-lock. For loading/unloading of containers to/from a horizontal transport vehicle, it is customary for the horizontal transport vehicle to drive to the exact bay in the block where the loading/unloading of the container will take place, as this reduces the amount of movement which the RTG has to do. An illustration of this process is visualised in Figure 2.6.

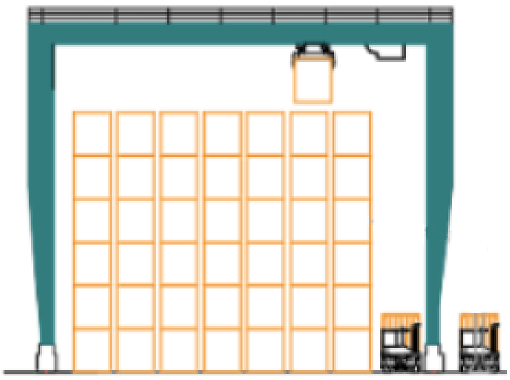

Figure 2.6: Illustration of a RTG transporting a container between the stack and an ATT

Most RTGs run on diesel engines, although there are also hybrid-electric and electric systems connected by a busbar. Most RTGs are also operated by a human in the cabin on the RTG, however there are also automated and tele-operated RTG systems. For this thesis, a human operated RTG is assumed.

2.2.4. Quay Crane (QC)

Quay cranes or ship-to-shore cranes, are large vehicles which move containers between vessels and (A)TTs. For this they utilise a similar spreader and lifting system as RTGs, but then with a much farther reach in order to move containers from and to vessels. QCs exist in many different sizes and configurations, which are mainly dependant on the size of vessels able to berth at the quay. A skilled operator is required to steer these types of cranes. They are mostly operated out of a cabin located next to the spreader on the boom of the crane, which follows the movement of the spreader in order to have a better view on the container position. There also exist tele-operated an autonomous QCs, although the majority are still operated from the onboard cabin. For this thesis, a human operated QC is assumed.

QCs can move parallel to the quay by driving on two rails which are embedded into the quay. This parallel movement is needed in order to position the QC to access the different container bays on the vessel. (A)TTs move on the quay lanes which lie in between the rails of the QC and stop at the required vessel bay so the QC can move the container between the vessel and (A)TT. A diagram of a quay crane is visualised in Figure 2.7.

In terms of terminal efficiency, QC utilisation rate is often the most important metric. This is especially true for the measurement of horizontal transport efficiency. QCs are almost always the most expensive piece of machinery on a terminal, so terminal operators want to maximise their utilisation as to maximise their return on investment on these QCs. Terminal operators also want vessels to be loaded and unloaded as fast as possible, as to be able to service as many vessels as possible in a given time. A higher QC utilisation rate will often translate into faster loading and unloading times for vessels.

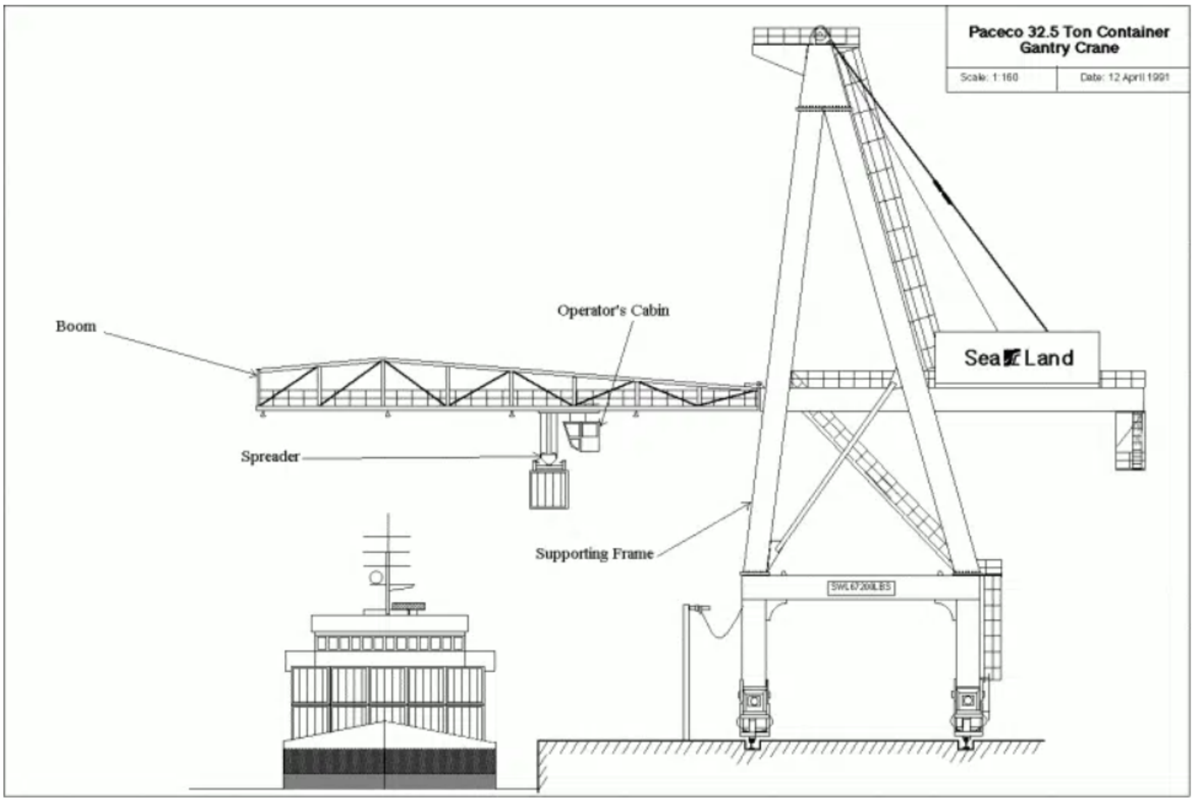

Figure 2.7: Diagram of a quay crane (Wankhede, 2021)

2.2.5. Road Truck

As the name implies, road trucks are trucks that ordinarily drive on public roads. They are not part of the vehicle pool that is owned by the terminal and are driven by truck drivers which are employed by external trucking companies. They enter and leave the terminal trough the gate and for the most part, their only business at the terminal is delivering and/or picking-up a container. They typically want to spend as little time as possible on this.

They mostly have to keep themselves to the same set of traffic rules on the terminal as the internal horizontal transport vehicles, however as the road truck drivers are not employed by the terminal, this is harder to actually enforce. Unlike (A)TTs, road trucks do not drive on the quay road or apron, as they deliver/pick-up their containers at the yard only. As such, road trucks only drive from the gate, over the highways and yard roads, to their assigned yard bay, and then back to the gate again.

2.3. Terminal Operations

Within a terminal, there are several different processes which are operational at a given time. For this study, only four of these processes will be included into the scope. These are the loading and unloading of containers onto and from vessels, and the loading and unloading of containers to and from road trucks. All of these processes feature some sort of horizontal transportation component, either with a road truck or with an ATT.

The horizontal transport flows of these processes are visualised on a map of a terminal in Figure 2.8, with the two processes moving containers between the vessel and the yard being displayed by the blue arrows, the two processes moving containers between the road trucks and the yard by the green arrows. Occasionally (A)TTs also drive between two different yard stacks, if they have a drop-off and pick-up job scheduled directly after each other or when they have to pick-up/drop-off multiple containers at once. This process is displayed by the yellow arrow. These visualisations are just three single examples of possible flows in the terminal, during operation multiple and combinations of these flows will be running at the same time with overlaps on the utilisation of the road network.

The scoped operations are of course only a simplification of the real world operations, but they do capture the essence of what happens on an RTG-based terminal. Operational factors which are known to play a role in the real world but which are excluded from this study include: container loading/unloading to/from rail, fuel/battery consumption/refueling, employee scheduling and maintenance operations. Also are RTGs bound to their stack block and are not allowed to move between blocks in this study, while they do move between blocks in real life operations. In addition, features this study more RTGs per block than is usual for this scale of operations, in order to mitigate queues at the RTGs as a bottleneck.

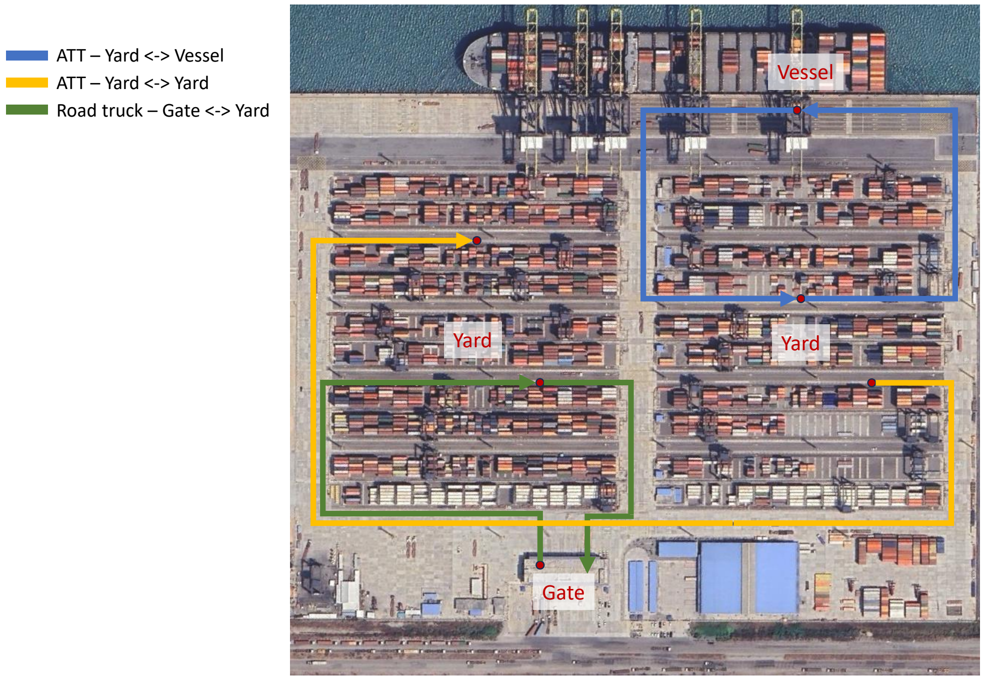

Figure 2.8: Example routes of (A)TTs and road trucks in a terminal

2.3.1. Vessel loading/unloading

All containers that enter of leave the terminal via the seaside follow the processes visualised in Figures 2.9 and 2.10 respectively. The visualised process is only applicable to flows where one (A)TT would transport one container at a time. If an (A)TT would have a multi container job, it will have to repeat part of the process for the second container.

It is notable that the processes for both the incoming and outgoing containers are nearly identical but then in reverse. There are four main actors in these two processes: the QC, (A)TT, RTG and twist-lock engineers. For this study, the twist-lock engineers will be seen as part of the QC. There are vehicle interactions between the (A)TT and the RTG, and the (A)TT and the QC. Both these interactions occur when the (A)TT is standing still.

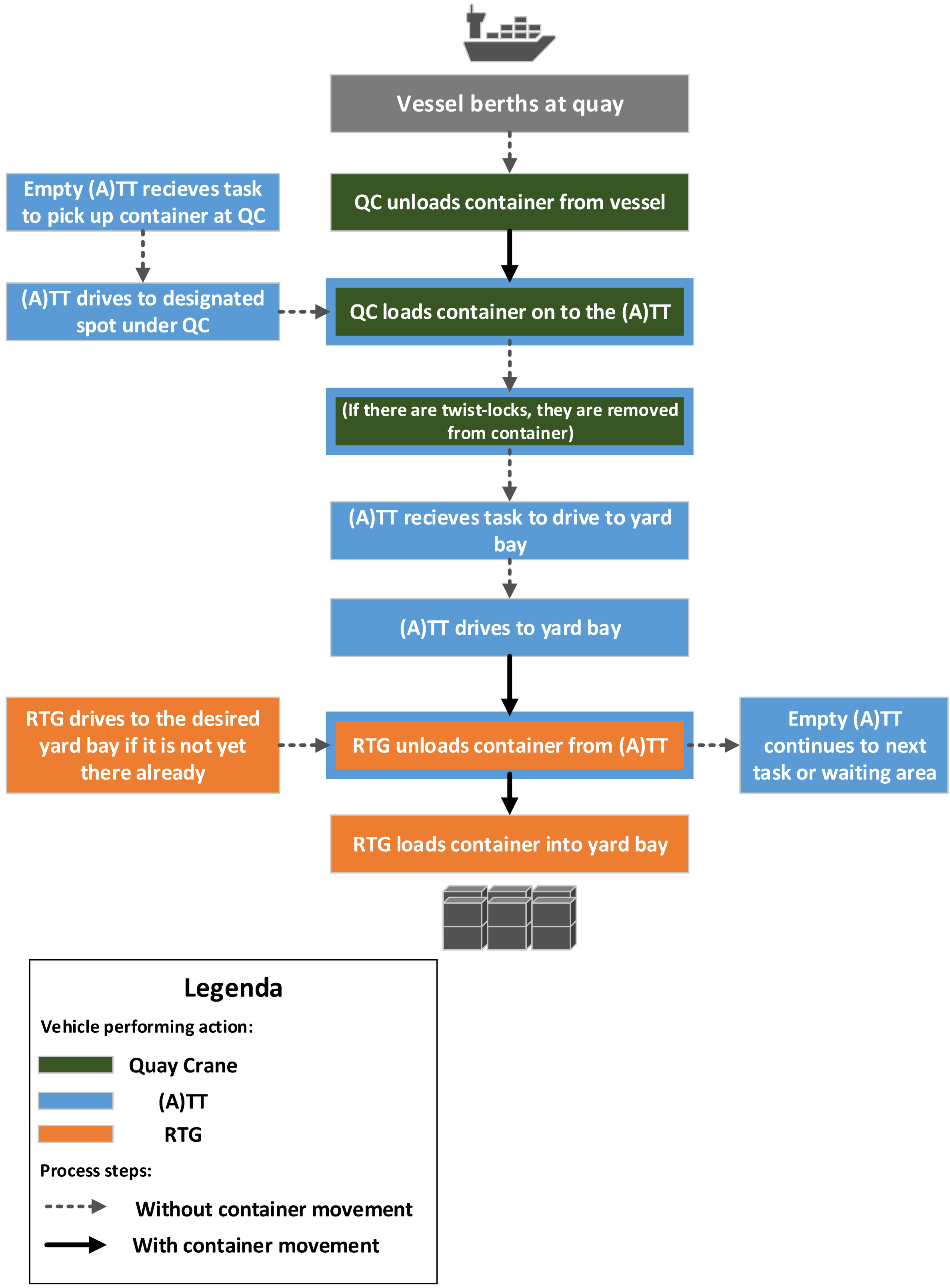

Figure 2.9: Process of moving containers from the vessel to the yard

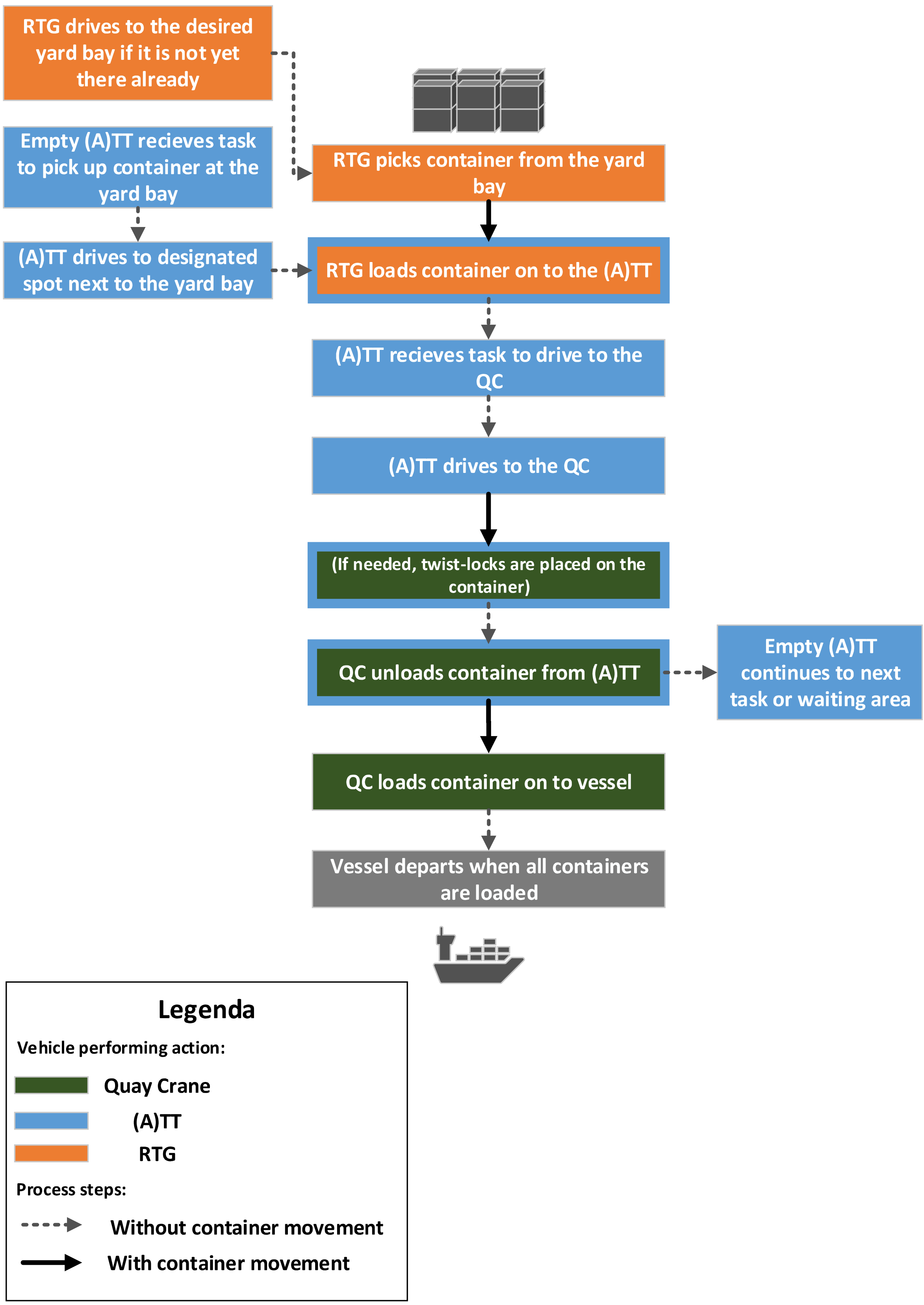

Figure 2.10: Process of moving containers from the yard to the vessel

2.3.2. Road Truck loading/unloading

All containers that enter or leave the terminal via the landside follow the processes visualised in Figures 2.11 and 2.12 respectively. Just as with the processes mentioned for the vessels, are the incoming and outgoing processes nearly identical in reverse. There are some differences with the processing at the gate for entering and leaving containers, however these are not relevant enough to be included into the scope of this study. There are only two actors in these two processes, these are the RTG and road truck. These only interact with each other when the road truck is standing still.

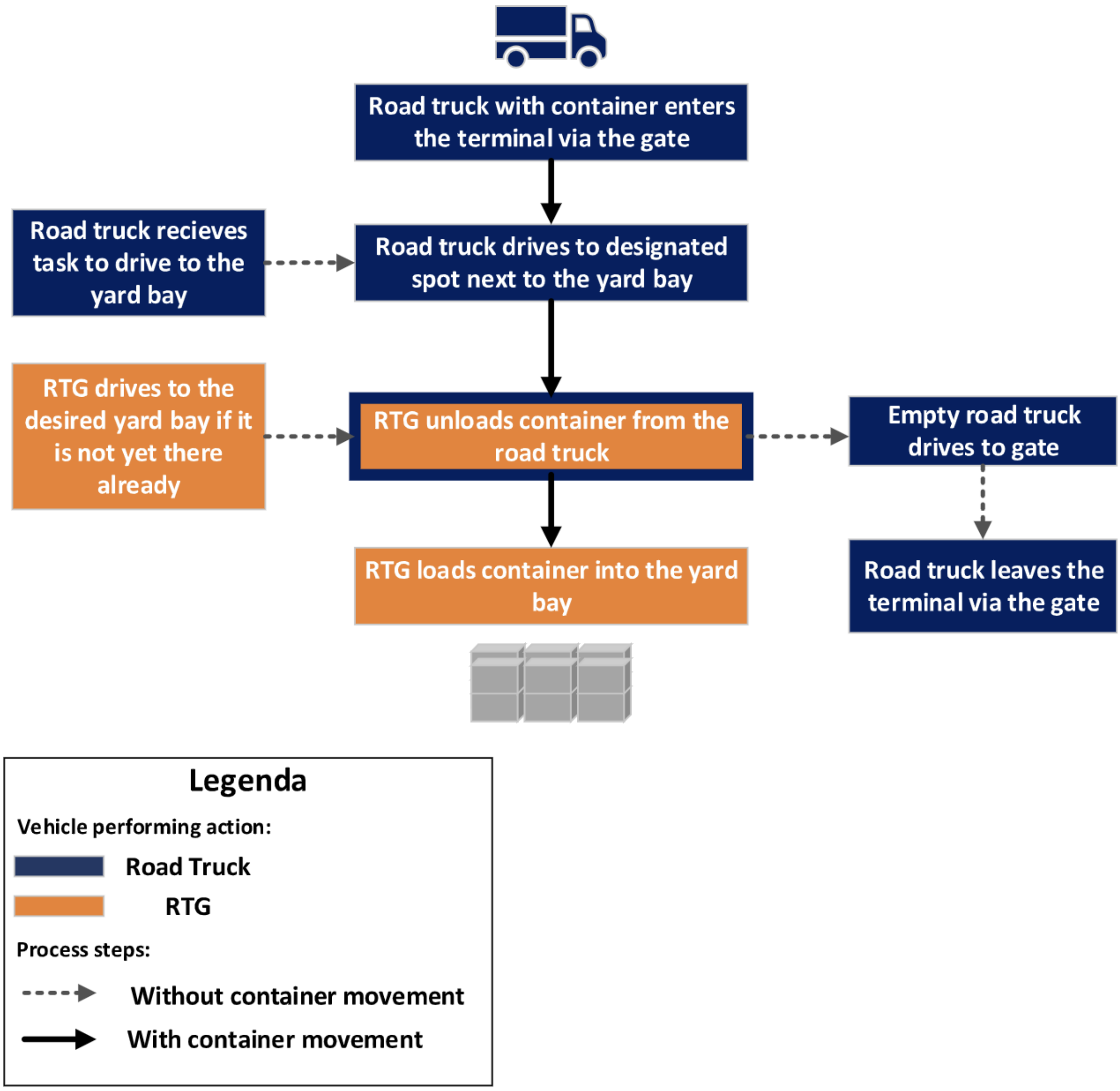

Figure 2.11: Process of moving containers from the terminal gate to the yard

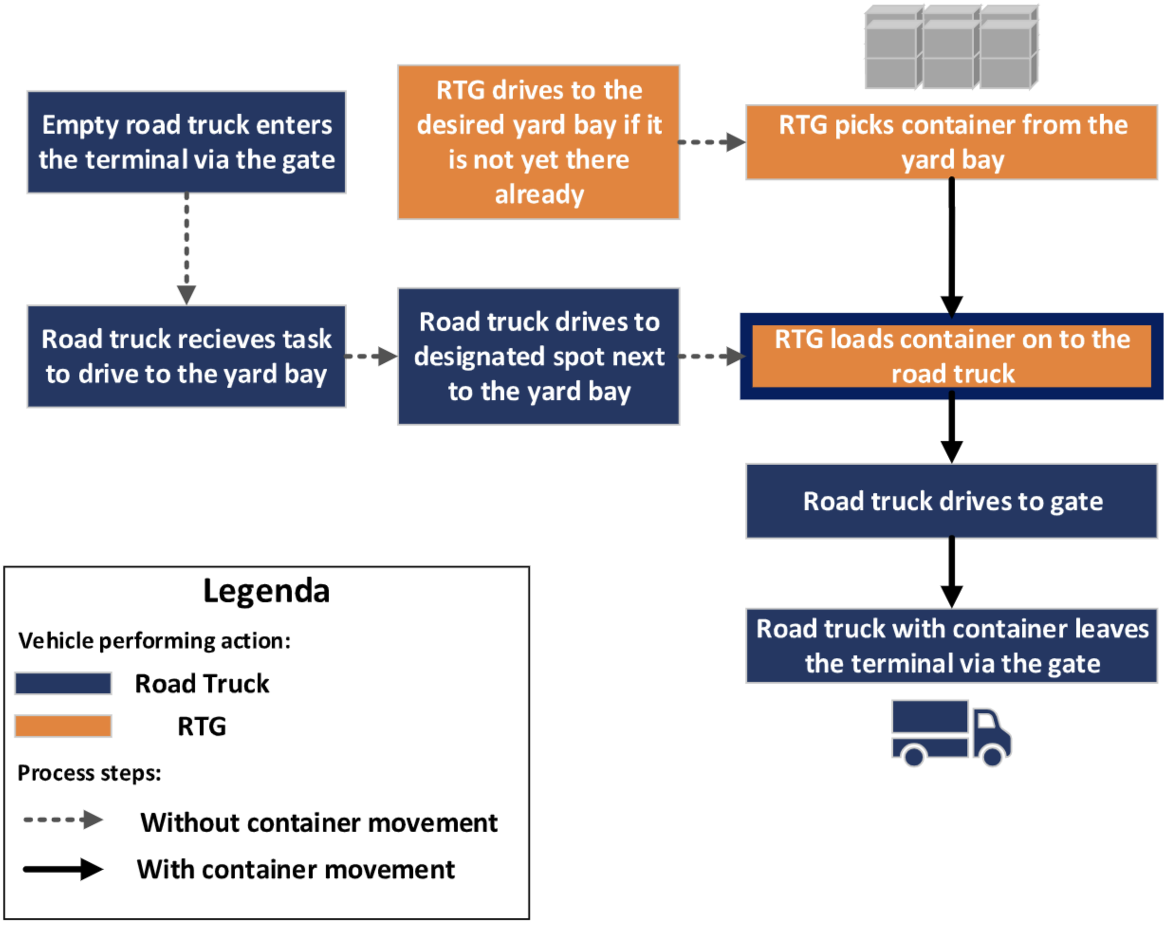

Figure 2.12: Process of moving containers from the yard to the terminal gate

2.4. Operational Performance Measurements

From the standpoint of the terminal operator, one metric of operational performance is by far the most important, which is the container throughput of the terminal in TEU (Twenty Foot Equivalent Unit). Which measures how many twenty foot containers the terminal could handle within a given time horizon (one forty foot container counts as 2 twenty foot containers or 2 TEU). As this is dependant on the twenty foot container to forty foot container ratio, this is important to keep into account for interpreting measurements. As each terminal is unique, each terminal has its own TEU throughput KPIs on which it measures its performance. Ports and Harbors, 2016 has reported a set of KPIs for TEU throughput including: TEU per meter of quay, TEU per Hectare, TEU per quay crane, TEU per stevedoring worker, TEU per RTG, and TEU per horizontal transport vehicle.

In some cases, containers are used as a measurement unit instead of TEU. This is again up to the terminal operator to decide which measurement unit is used. Some other operational performance measurements of container terminals are defined by Pham and Nguyen, 2022, which include:

- Average number of quay crane movements per hour
- Average yard dwell time of a container
- Average road truck turn around time
- Average gate dwell time for road trucks

Next to these, operational performance measurements may also include others, like overall power consumption per TEU or vessel dwell time. It is entirely up to the terminal operator to choose performance measurements which fit their terminal best.

2.5. Conclusions on the Container Terminal System Analysis

In the conclusion of this chapter, an answer is formulated to sub-question 1: *How does an RTG-based terminal system function, which operational processes are present on it and how can the operational performance of it be measured?*

An RTG-based container terminal is a terminal where RTGs and (A)TTs are used as equipment for the transportation of containers within the terminal. The terminal typically features a parallel layout, which means that the stack blocks in the yard are positioned parallel to the quay. The stack blocks in the yard are accessible through the yard roads, which in turn are connected by perpendicular running highways. These highways then connect to the apron and the quay road on the seaside, and the back-road and gate on the landside.

The HDVs which operate on the analysed terminal consist out of: road trucks, RTGs and QCs. The only autonomous vehicles which operate within this system are ATTs. The horizontal transport of containers is facilitated by ATTs for container moves within the terminal, and by road trucks for the horizontal transport of containers entering or leaving the terminal by public road. RTGs are used to move containers between horizontal transport vehicles and the yard stacks, and QCs are used to move containers between the vessel and (A)TTs.

Within the scope of this analysis, four operational processes which occur on an RTG-based terminal were discussed. The process of moving a container from the vessel into a stack block, and vice-versa, using a QC, an (A)TT and a RTG. As well as, the process of moving a container from the gate into a stack block, and vice-versa, using a road truck and a RTG.

In terms of operational performance measurements of container terminals, the most relevant one for terminal operators is found to be the container throughput of the terminal, measured in TEU or containers in a given time horizon. Further categorisations within container throughput, like TEU per QC or TEU per RTG could also be used. Other non-strictly-throughput based performance measurements may include average QC movements, average yard dwell time of a container, average road truck turn around time and gate dwell time.

3

Autonomous Terminal Tractor as a System

In this chapter, the ATT is analysed from a systems engineering point of view. First, an overview is given of the state-of-the-art of ATT developments as well as some context on the levels of automation. Then, an analysis is conducted on the sensors implemented in the perception module of ATTs, as well as on the control structure of ATTs integrated in a container terminal. Then, the operations and vehicle interactions are analysed from the perspective of an ATT. Lastly, an analysis is conducted on the ATT-only and mixed traffic intersections which are present on an RTG-based terminal. By conducting these analyses, an answer can be formulated to sub-question 2: *How does the internal system and control structure of an ATT function, and how does the ATT interact with other vehicles?*

The ATT has been developed as an alternative to both the human driven TT and the AGV, for RTG-based terminals which want to automate their internal horizontal transport but also want keep their parallel terminal layout. In this parallel layout, road trucks and ATTs will have to drive on the same road network and each separate ATT should be able to see all other vehicles and obstacles on its path, and determine its actions accordingly.

3.1. Levels of Automation

Before delving into the ATT itself, some context around vehicle automation is in order. To differentiate between different stages of vehicle automation, SAE has defined the 6 levels of driving automation, these levels are visualised in Figure 3.1. Levels 0, 1 and 2 define support features for human drivers. Levels 3 and 4 define semi-automated vehicles where either humans need to intervene in certain situations or where the autonomous vehicle can only function in certain conditions. Level 5 would constitute a completely autonomous vehicle (ORAD-Committee, 2021). Most manufacturers of current state-of-the-art ATTs claim that their vehicles can operate at level 3 or 4.

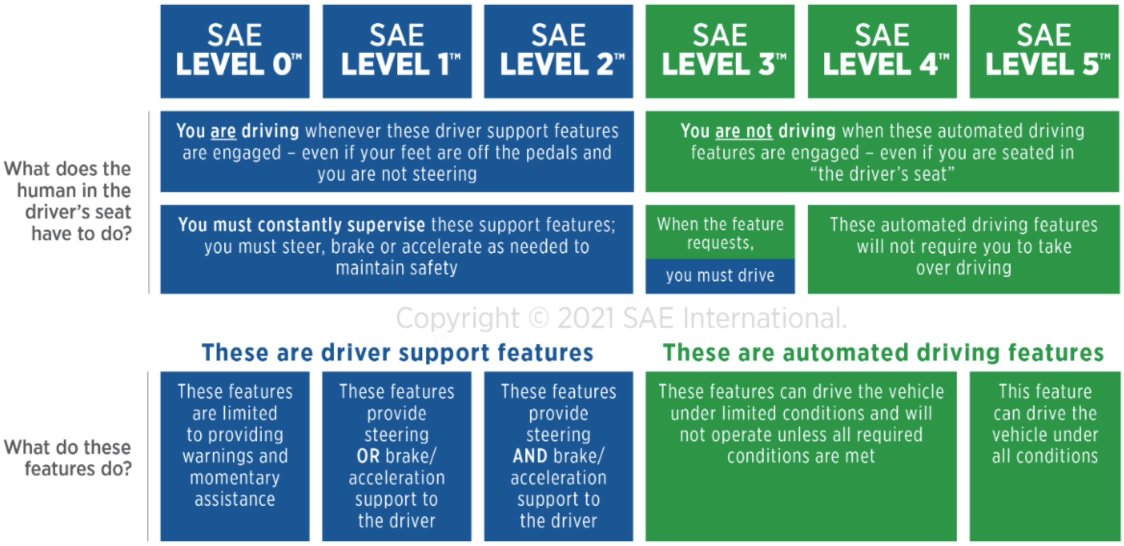

Figure 3.1: SAE Levels of Automation (SAE-International, 2021)

3.2. State-of-the-art

There are currently several companies developing their own ATT concepts. Some of them use already existing TT hardware with drive by wire capabilities, onto which they install a sensor and communication - actuation kit. Other companies have developed their own tractor hardware from the ground up to include all modules needed for autonomous operations. As these developments are currently the state-of-the-art, an overview of the current ATT developments by companies will be given. Some of the ATT developments have quite a limited amount of information available about them. The overview features the publicly available information about these ATT developments.

3.2.1. Easy Mile - EZTug

Figure 3.2: EZTug in Lineage Logistics Terminal Vlissingen (Terberg-Special-Vehicles, 2022)

EasyMile is a French autonomous vehicle technology company, which has partnered with Terberg to develop their EZTug ATT, as visualised in Figure 3.2. The EZTug is a retrofitted Terberg YT203EV TT, featuring a sensor set developed by EasyMile. It consists out of cameras, LiDARs, radar, GPS/RTK (real-time kinematic) positioning, Inertial measuring Unit and odometry. EasyMile claims level

4 automation with their EZTug in a mixed traffic environment with autonomous, remote controlled and manual operations possible (EasyMile, 2023). The EZTug has been tested as a proof of concept in May 2022 at the Lineage Logistics Terminal in Vlissingen (NL) (Terberg-Special-Vehicles, 2022), as well as tested its feasibility and effectiveness in June 2024 at the Port of Helsingborg (SE) (EasyMile, 2024) and demo tested at the APMT MVII terminal in Rotterdam (NL) in April 2024 (APM-Terminals, 2024).

3.2.2. Westwell/Qomolo Q-Truck

Figure 3.3: Q-Truck in Laem Chabang Terminal D (Container-News, 2020)

Westwell is a Chinese company which has developed their own version of an ATT in 2018, called the Q-Truck (as pictured in Figure 3.3), under the Qomolo brand. In 2020, they have started mass production of the vehicles (Pandaily, 2022). They claim that the Q-Truck is capable of level 4 automation in a mixed terminal environment, and are currently working on achieving level 5 automation. Which makes it possible for it to function fully autonomously while within the terminal area. The ATT would achieve this by utilising its sensors to detect other vehicles and obstacles, and artificial intelligence to decide which action is then most appropriate to take (Hutchisonports, 2021). The sensors on the Q-truck include multiple LiDARs, cameras, ultrasonic radars and Millimeter Wave Radars, although the exact number and orientation is unspecified (Westwell, 2022).
The Q-truck has a set of behaviours which it will execute when it encounters certain scenario's. These include: queuing, following other vehicles, cutting in line, cutting out of line, overtaking other vehicles, side-passing objects and safety stop before objects. These behaviours are handled by the artificial intelligence system within the truck, while the general route planning is handled by a central planning system (Zhang, 2022). In case of emergency, there is a possibility to remotely control the vehicle, but as there is no cabin onboard, manual operation of the vehicle is impossible (Westwell, 2023).

There are currently three CT sites where the Q-truck is operational, these are:

- Hutchison Ports Thailand - Laem Chabang Terminal D, with 6 ATTs implemented on 26/04/2020 (Container-News, 2020).
- CSP Abu Dhabi (UAE), with 6 ATTs implemented on 06/07/2021 (AbuDhabiPorts, 2021).
- Hutchison Ports Felixtowe (GB), with 2 ATTs starting from 09/2023 and plans to expand to 100 in the future (Port-Technology-International, 2023).

3.2.3. AI Drivers - AIRS

Figure 3.4: Terberg YT223-T3 retrofitted by AI drivers (AI-Drivers, 2023)

AI Drivers is a British software development company, which has been developing an autonomous retrofit-kit for manual Terberg TTs since 2019, and launched their product AIRS on 29/11/2022. One of the retrofitted Terberg models is the YT223-T3, which is featured in Figure 3.4 (AI-Drivers, 2022). The kit developed by AI Drivers features 5 cameras, 4 radars and 2 LiDARs. These sensor units are placed on the cabin of the truck and provide the system with a near 360 degree view, only objects directly behind the trailer can not be seen. With the kit, AI Drivers claims that the truck could function with level 4 autonomy in a container terminal environment. Next to autonomous operation, the vehicle can also be remote or manually controlled by a human (AI-Drivers, 2023).

There are currently two sites that are testing the AIRS system:

- PSA Pasir Panjang Terminal Singapore, with trails running since 2019 and 2 ATTs implemented on 17/03/2021 (Ghani, 2021).
- AD Ports Zayed Abu Dhabi (UAE), with an unspecified amount of ATTs implemented on 2/08/2022 (Port-Technology-International, 2022)

3.2.4. Gaussin - APM 75T Autonomous

Figure 3.5: Photo of the APM 75T Autonomous (Gaussin, 2023)

Gaussin is a French vehicle manufacturer, which has in-house developed their own ATT, called the APM 75T Autonomous, as pictured in Figure 3.5. It is an autonomous adaption of their APM 75T vehicle,which is manually operated. The vehicle comes in both a battery electric and a hydrogen fuel-cell version. The vehicle is level 4 autonomous within a mixed traffic gated terminal, and can be remotely operated. There is no possibility for manual operations with this vehicle (Gaussin, 2023).

The APM 75 Autonomous has been developed at the testing site of Gaussin at Hericourt, and the first/only implementation of this ATT is GWC Al Wukair Logistic Park in Qatar, where 2 tractors are operational since Q1 of 2022 (Gaussin, 2021).

3.2.5. Fernride

Figure 3.6: Fernride ATT at HHLA TK Estonia (Fernride, 2023a)

Fernride is a German company, specialised in teleoperated vehicles. They have developed their (semi)-ATT in collaboration with Terberg, pictured in Figure 3.6. Their vehicle is less autonomous than their competitors, with obstacle handling still mainly being done by a human teleoperating the vehicle. Their standpoint is that of semi-automation, with their aim being 80 to 90 percent automation (Fernride, 2023b). Fernride has a deal with Terberg to manufacture 100 of their vehicles in a series-production in 2024 (Terberg, 2023).

There are currently two projects with Fernrides semi-ATTs:

- HHLA TK Estonia: with trails running since January 2023 with one vehicle and 2 operational vehicles since June 2023 (Fernride, 2023a).
- DB Schenker Tilburg (NL): With one vehicle testing since 2022 (Jong, 2022).

3.2.6. Senior/Si Nian Zhijia - Xizhong

Figure 3.7: Senior ATT at Ningbo port (Senior, 2023)

Senior (also known as Si Nian Zhijia) is a Chinese company, specialised in autonomous terminal vehicles. They have developed their Xizhong ATT on the hardware of a BYD truck, pictured in Figure 3.7. Their sensor suite is a bit simpler than the previously mentioned ATTs, as the only utilise LiDars and cameras (Senior, 2023). Their ATTs are currently only operating in Chinese container terminals , and they have reportedly around 100 ATTs in operation at the ports of Ningbo, Tangshan Zhuhai, Suzhou, Xiamen and Suqian (NikkeiAsia, 2022).

3.2.7. Autonomous Solutions Inc. and Phantom Auto - Smart Yard Shifting

Figure 3.8: Picture of the ASI Smart Yard Shifting ATT (ASI, 2023)

Autonomous Solutions Inc. (ASI) is an American company which develops a whole variety of autonomous vehicles and robots, as well as control software for these applications. They have collaborated with Phantom Auto, which is an American remote operation developer, to build their Smart Yard Shifting ATT, pictured in Figure 3.8. This ATT is built on the Terberg AutoTug platform. Just like Fernride, their ATT is more focused on remote operations than being fully autonomous (ASI, 2023), (Phantom-Auto, 2023).

3.2.8. Volvo - Vera

Figure 3.9: Picture of Volvo Vera (Cargo-Partnerl, 2019)

Volvo is Swedish automotive manufacturer, which has in-house developed their Vera autonomous truck in 2018, pictured in Figure 3.9. Vera is a bit different from the other ATT models mentioned in this section, as Volvo has intended for Vera to function in both a mixed terminal environment as on public roads. As such, the first and currently only implementation of Vera is in connecting DFDS' logistics center to the APM Terminal in Gothenburg, which is a route of approximately 4 km over a public industrial road. next to that Vera should also be able to cooperate in the APM Terminal (Volvo, 2019).

3.2.9. Other developments/concepts

The aforementioned developments all were either implemented or tested at a real-life terminal, and had working products or prototypes. There are however also some companies with ATT concepts which are not yet so far in development.
One of them is Streetdrone, which has a similar semi-ATT system to Fernride. They are planning to test their vehicle in the Kramer Groups City and Maasvlakte terminals in Rotterdam in 2023/2024 (Giurea, 2023).
Another is Outrider, which is mainly focusing on ATTs in yards and logistics centers, and has developed their own concept. Not a lot is publicly available about their project (Outrider, 2023).
There is also Embotech, which is developing an ATT for use in both port terminals and distribution centers. They have built a working prototype of their ATT on the Terberg EZTug platform (Embotech, 2023), and has been demo tested at the APMT MVII terminal in Rotterdam (NL) in April 2024 (APM-Terminals, 2024).
Lastly there is Konecranes, which is developing their ATT concept together with Terberg (Konecranes, 2023).

3.3. Sensors

The sensors of an ATT are akin to the eyes of a truck driver, it is through them that the ATT perceives the environment it is driving in. Therefore, utilising the right types of sensors is important for the correct functioning of an ATT. ATT manufacturers all have their own sensor suites and sensor combinations which they use in their developments. A possible arrangement of sensors is visualised in Figure 3.10, which features the Embotech sensor suite.

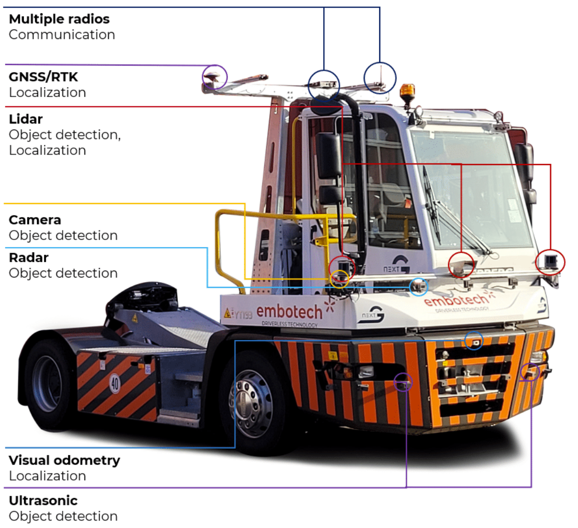

Figure 3.10: Sensor diagram of the Embotech sensor-suite for automated driving (Embotech, 2023)

In Table 3.1, an overview is given of the sensors used in the ATTs presented in Section 3.2. Not all ATT manufacturers have published information about the sensors they have used, and even among the ones which have published theirs, some go no further than just mentioning which sensors are used without disclosing the amount or arrangement. As such the table is structured as follows: If the amount of sensors is known, then these are mentioned in the table. If it is only known whether or not a sensor is used, then this is indicated by just "Yes" or "No", with No meaning that that sensor was not mentioned by the manufacturer while other sensors were. If a manufacturer has not disclosed any information about the sensors, then it is indicated by "-".

ATT	LiDAR	Camera	(mm Wave) Radar	Ultrasonic	Other sensor
EasyMile	Yes	Yes	Yes	No	GNSS, IMU and Odometry
Westwell/Qomolo	Yes	Yes	Yes	Yes	GPS & 5G Receiver
AI Drivers	2	5	4	No	No
Gaussin	Yes	Yes	Yes	No	No
Fernride	-	-	-	-	-
Senior/Si Nian Zhijia	Yes	Yes	No	No	No
ASI/Phantom Auto	Yes	Yes	Yes	No	No
Volvo	-	-	-	-	-
Streetdrone	-	-	-	-	-
Outrider	Yes	-	-	-	-
Embotech	3	4	1	1	INS and Visual Odometry
Konecranes	-	-	-	-	-

Table 3.1: Table summarising the available information about sensors on ATTs per manufacturer

From the available sensor information presented in Table 3.1, it can be concluded that three sensors are almost always part of the sensor suite: LiDARs, cameras and (mm wave) radars. As these three sensors are so widely used in ATTs, their workings will be shortly explained in the following parts.

3.3.1. LiDAR

LiDAR stands for Light Detection and Ranging, and this type of sensor measures its distance to nearby objects by emitting an infrared laser pulse and measuring how long it takes before the laser pulse is reflected by an object and is returned to the receiver sensor on the LiDAR module. By measuring the time-of-flight of the laser pulse, the LiDAR can give a distance range between it and the nearby object. This process is also visualised in Figure 3.11.

By rotating the laser sender and receiver for a certain amount of rotations per minute and having senders and receivers under different angles, a 3D profile of the environment can be created using a LiDAR. The laser beams emitted from the sender are safe for the eyes and can detect objects to up to approximately 300 m, dependant on LiDAR manufacturer (Vargas et al., 2021). The maximal rotational speed of most LiDAR sensors for automotive applications is 20 Hz, meaning that the 3D image created by the LiDAR is updated 20 times per second (Velodyne, 2019), (Ouster, 2023).

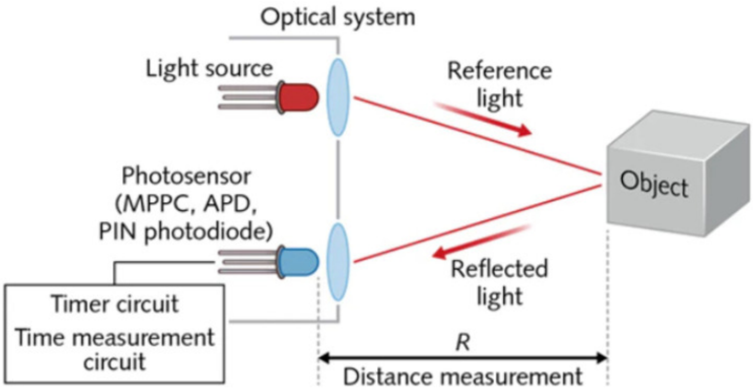

Figure 3.11: High-level block diagram for time-of-flight LiDAR system (S. and, 2017)

3.3.2. Camera

Cameras used on ATTs are in essence quite similar to the ones on a smartphone. They capture light-waves which are radiated by the sun or external light source and reflected by an object. By capturing these waves, the output of a camera allows for the differentiation between colors of the visible (and sometimes also IR) spectrum, which allows for object detection via image recognition. Two cameras can also be used to create a stereoscopic vision with a depth of field (Vargas et al., 2021).

3.3.3. mm Wave Radar

Radar stands for Radio Detection and Ranging, and just as the name implies, it utilises a similar sending and receiving process to measure out the distance between the sensor and an object as a LiDAR. Only instead on laser pulses, it are short, medium or long range radio waves which are used, dependant on the distance and accuracy needed (Vargas et al., 2021).

3.3.4. Sensor Fusion

LiDARs, cameras and radars all have certain strengths and weaknesses, by fusing the outputs of these sensors, the strengths of one sensor can cover the weakness of another. The outputs of LiDARs and radars for example, are not detailed enough to be used for object recognition, but that of a camera is. The output of a camera is than again unable to detect objects in a low lighting environment, while LiDAR and radar do not have the same issue. LiDARs and radars are also used in AVs for the sake of redundancy, meaning that when one of the sensors would be unable to detect an object or vehicle, then the other one would still have detected it (Yeong et al., 2021).

3.4. Control Structure

Because ATTs are autonomous functioning vehicles, they can make certain decisions by themselves. However they are also still part of the vehicle system of a container terminal, so certain decisions will be made for them by an agent on a higher control level. This type of control architecture where there are multiple layers of multiple controllers is called multi-agent multi-layer control (Negenborn and Hellendoorn, 2010). Dependant on the ATT manufacturer, the control structure of the ATT layer could be a distributed (ATTs can communicate directly to each-other) or decentralised control (ATTs can only communicate with an agent on the layer above it). ATT developers have stated that they use a decentralised control structure for their ATT fleets, so for this analysis, a decentralised control structure is also assumed. A flow chart featuring all components in the control architecture of a system of ATTs, is visualised in Figure 3.12. Further explanation on what these components do and how they interact with each other will be explained in the following subsections.

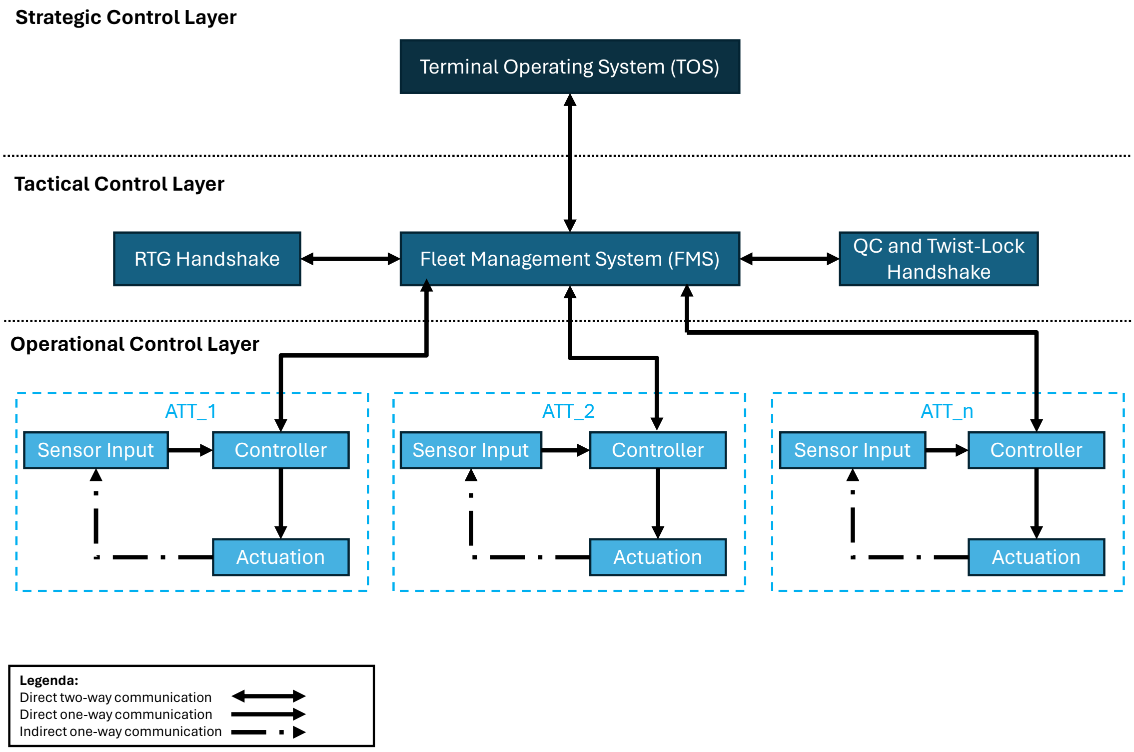

Figure 3.12: Control structure of a system of ATTs

3.4.1. Control Levels

There are three control layers within this system. The highest is the strategic control layer, which is responsible for the planning of container placement and assignment of vehicles to tasks within the terminal. In this layer the terminal operating system is situated.

Then there is the tactical control layer, which is responsible for the routing of vehicles as well as facilitating inter vehicle collaboration. In this layer, the fleet management system is the main routing and communication component. It communicates constantly with all ATTs in terms of their routes, current coordinates and intersection management, and communicates the finishing of jobs in the form of handshakes with the RTG, QC and twist-lock handlers.

Lastly there is the operational control layer, which is responsible for the vision and actuation of each ATT. Here all ATTs are separate agents within the layer, and as the ATTs can not directly communicate with each other, they are working within a decentralised control structure.

3.4.2. Terminal Operating System

The terminal operating system or TOS is situated in the strategic control layer, and is the central planning and decision making system in a container terminal. Dependant on which TOS software is used, it can do everything from documentation handling to vehicle maintenance planning. As such, only the relevant features of the TOS for this study will be discussed.

As a central planning system, the TOS dictates how containers are loaded and unloaded to and from vessels, where the containers should be stored in the yard, and which equipment should handle each container. It also keeps track of where all containers and equipment vehicles are, as well as registering which road trucks have entered the terminal (Slashdot, 2023).

The TOS gives a specific order to the fleet management system about which ATT should fulfill a container pick-up and delivery request and to which container bay and/or QC the ATT should drive in order to fulfill the request. The TOS receives in turn from the fleet management system the current operational status and location coordinates of each ATT.

3.4.3. Fleet Management System

The fleet management system (FMS) is situated at the tactical control layer, and functions as a sort of translator between the TOS and the ATTs. Dependant on the ATT manufacturer, the ATT has to be directed by a FMS supplied by the manufacturer or by a FMS provided by a third party. It will get instructions from the TOS on which ATT should go where and it will translate that into a command and send it to the ATT in question. All ATTs constantly update their location coordinates to the FMS. The FMS is situated in a centralised location, and communication between the ATT and FMS is transmitted the local Wi-Fi network of the terminal.

A separate part within the FMS is the intersection management system (IMS), this system regulates the access of ATTs to the ATT-only intersections. This is needed as the ATTs are unable to coordinate this between themselves. How the IMS functions is largely dependant on the chosen intersection strategy, this is further elaborated in Section 5.6. For the mixed-traffic intersections, the FMS applies a different set of rules for the ATTs. These are further elaborated in Section 3.8.
The FMS also handles the handshakes between the ATT, and the RTG, QC and twist-lock engineers.

3.4.4. Controller

The controller of the ATT is responsible for the operational control layer, it acts as the brain of the ATT and is situated on the ATT itself. Every ATT has its own controller, and it will decide which actions the ATT will undertake in terms of acceleration and braking. It does this by incorporating commands from the FMS and inputs from the various sensors into its decision making process. To guide this process, the controller has its own decision making logic, a design for this logic can be found in Section 5.3.2.

Dependant on the ATT manufacturer, controllers can communicate between each other and share location data on where all ATTs are currently located, which makes this control layer either distributed or decentralised. In the base case of this study, a decentralised control structure is assumed, so controllers can not communicate between each other, and will only share data like their location coordinates with the FMS.

The controller knows where the ATT is on the terminal using a mix of sensor input data. The controller software from EasyMile uses the data from the following six sensors:

- Lasers
- Cameras
- Radars
- Differential GNSS (Global Navigation Satellite System)
- Estimation using an Inertial Measurement Unit (IMU)
- Odometry

In order to obtain a location estimation with a level of precision to within millimeters of the exact location of the vehicle, in the six dimensions visualised in 3.13 (EasyMile, 2023).

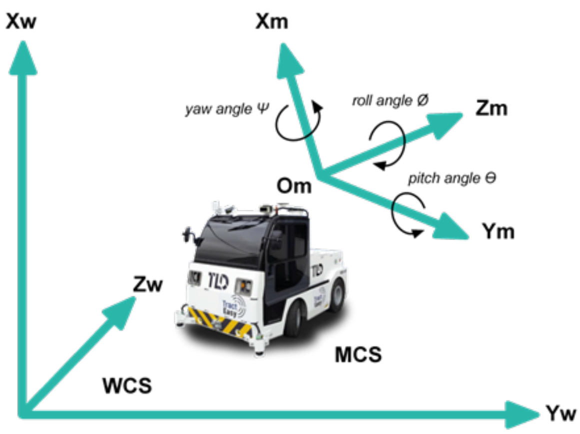

Figure 3.13: Illustration of Radar/Cameras/Lidar localization for the EZTow vehicle (EasyMile, 2023)

3.4.5. Sensor Input

The sensors of the ATT feed a constant stream of data into the controller, and it is the task of the controller to recognise other vehicles and objects from the sensor input. Section 3.3 explains further in-depth what the various sensors on an ATT are and do.

3.4.6. Handshakes

Handshakes are signals that are sent between two entities, to indicate the completion of an action. In the featured control structure, all handshakes with the ATTs, are coordinated by the FMS. This means that the controller will recognise when the ATT has reached its destination, and will send a handshake to the RTG, QC or twist-lock engineers that the ATT is ready to be serviced. When the RTG, QC or twist-lock engineers are done with their handling, they will send a handshake to the FMS to indicate that they are done, and that the ATT is allowed to start driving again.

3.4.7. Actuation

The ATT in this study, only has three actuators: accelerate, decelerate and steering. With these, the ATT is able to move to every position on the terminal. The controller has full control of these actuators, and uses them to execute the actions it has decided that the ATT will undertake. Control of the actuators can also be given to a tele-operator if that is required.

3.5. Operations from the ATT perspective

As the ATT is the vehicle of interest for this study, an overview is given of the operations, from the perspective of the ATT. Figure 3.14 contains all steps which are performed by the ATT during vessel loading and unloading.

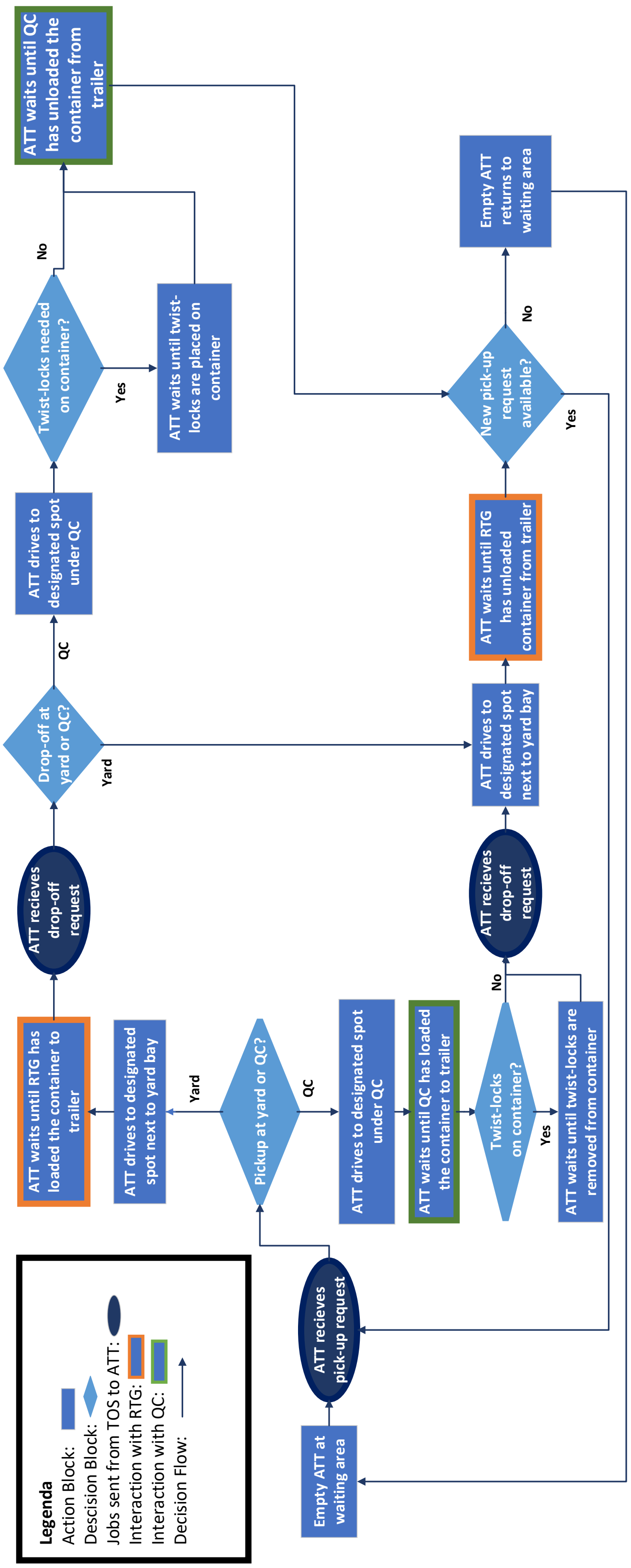

Figure 3.14: Diagram of all ATT actions within operations

3.6. ATT - Vehicle Interactions

In this section, all vehicle interactions on the terminal will be analysed from the perspective of the ATT. All interactions between vehicles which do not include an ATT in their interactive system, are left out of scope.

3.6.1. ATT and Road Truck

Road trucks are more limited in where on the terminal they are allowed to drive when compared to the ATTs. Road trucks are not allowed on the quay road, and should always take the shortest route from the gate to the assigned stack(s) and back (Hutchison-Ports, 2023). ATTs on the other hand, have no business operating around the terminal gate. As such, road trucks and ATTs only have possible interaction points at the highways, the yard roads and intersections of these two. A visualisation of the Operation areas of both road trucks and ATTs can be seen in Figure 3.15.

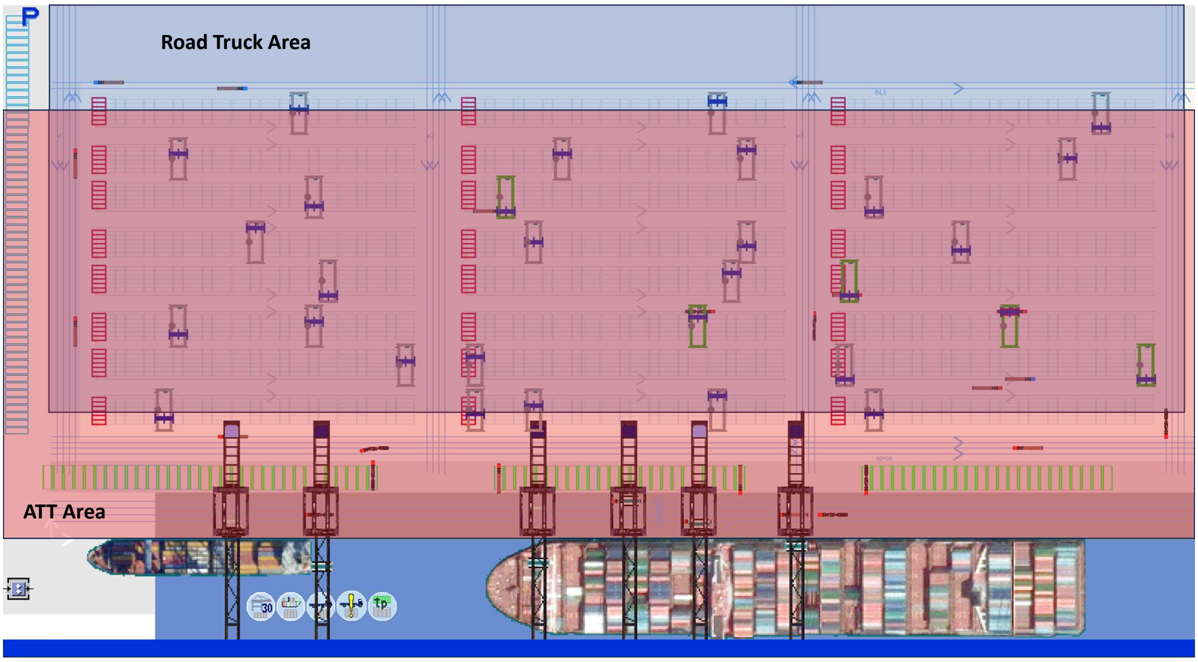

Figure 3.15: Operational areas of road trucks and ATTs

ATTs and road trucks have no direct way to communicate with each other, other than with turn signals and break lights. Some of the developed ATTs also have LED displays with which they can rely information to the road truck driver (Westwell, 2023). Road truck drivers have to rely on these signals in order to see which actions the ATT will take. ATTs on the other hand have to fully rely on their sensors do detect the direction and velocity of the road truck, in order to determine which action the road truck is undertaking.

3.6.2. ATT and ATT
Out of all vehicles, the ATT will have the most interactions with other ATTs. This is because ATTs can interact with each other at every stage of their process. This means that there are possible interactions on the highway, yard roads, quay roads and intersections of these.

ATTs are generally not capable to communicate with each other directly, but they can still communicate their positions and routes they are going to drive through the fleet management system (FMS) to other ATTs (Westwell, 2022). This means that ATTs have more information about each other than they have of road trucks, as such they can better anticipate on the moves of other ATTs.

There are also certain intersections at the seaside where only ATTs should drive. Because ATTs can communicate with their FMS, it can centrally regulate the flow of ATTs at these types of intersections, through the intersection management system (IMS). This way, more efficient intersection management strategies can be employed for these ATT-only intersections.

3.6.3. ATT and RTG
ATTs and RTGs can interact in two ways, there is the loading/unloading of a container by the RTG onto/from the ATT, and there is the RTG which is driving between stack blocks or along the yard road, and crossing the path of the ATT. For the loading and unloading, the ATT should be able to communicate to the RTG when that it has stopped at the desired yard bay. The RTG should subsequently be able to communicate to the ATT when it is done placing/removing the container and thus safe for the ATT to depart. This communication will be done in the form of handshakes between the FMS of the ATT and the RTG.

When moving between stack blocks, the RTG can move both parallel and perpendicular to the quay. Both of these moves will include crossing and driving on highways, which can hinder ATT movement there. RTGs can also drive up and down the yard road. This can hinder an ATT if it was planning on crossing the RTG lane at that moment. It has to be noted that while these situations do happen in real life operations, they will not be taken into account within the scope of the model in this thesis.

3.6.4. ATT and QC
ATTs and QCs can interact in two ways as well. Similar to the RTG, there is the loading/unloading of containers onto/from the ATT. For this the same kind of handshake between the QC and ATT vehicle controller is used to communicate when the ATT is stopped at the right spot under the QC and when the QC is finished with loading/unloading the container onto/from the ATT. QCs can also drive parallel to the quay on rails embedded in the quay road. ATTs always have to cross these rails when they want to reach the quay lanes. QCs do not often move parallel like this, only when it has to access another container bay of the vessel, but there is still the possibility that the planned path of an ATT crosses the parallel movement of the QC. Within the scope of the model of this thesis, these parallel QC moves are not included.

3.7. ATT-Only Intersections
At the intersections of the apron with the highways, lie intersections on which only ATTs would come during normal operations, the locations of these ATT-only intersections are visualised in Figure 3.16. Dependant on the particular terminal, these intersections could be either 4-way intersections or 3-way T-intersection, for this thesis a layout using the latter is assumed. Here the centre on the intersection is classified as a non-stop zone. ATTs will check if they can pass the intersection non-stop when they arrive at the queue line and the intersection management system only appoints ATTs to cross the intersection if they fulfill this requirement. This non-stop check is the main difference between this intersection and intersection commonly designed for CAVs, as this is usually not taken into account on public roads.

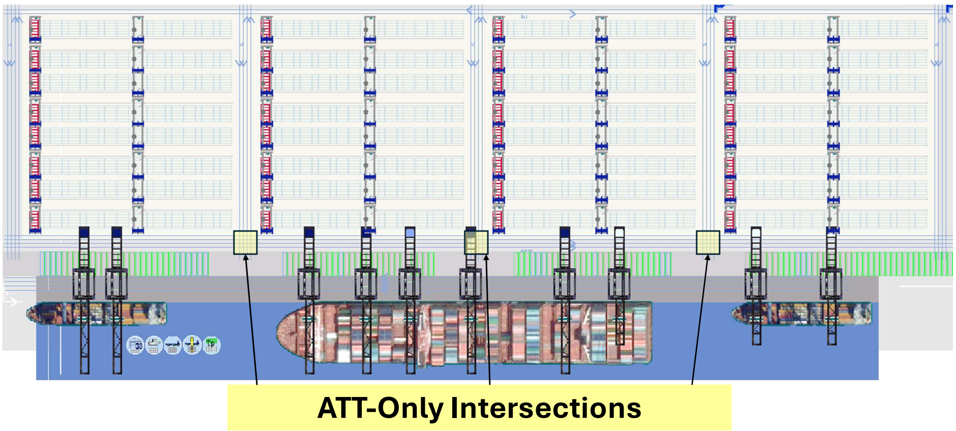

Figure 3.16: Locations of ATT-only intersections

When ATTs pass the detection line, they are added to the queue of the intersection. They are instructed to drive until the queue line and stop there, unless they are cleared to enter the intersection. A layout of an apron-highway intersection is visualised in Figure 3.17. The possible routes an ATT can take at the intersection, which are included in the scope of this study, are visualised in Figure 3.18. Do note that this does not include all physically and operationally possible routes at this intersection.

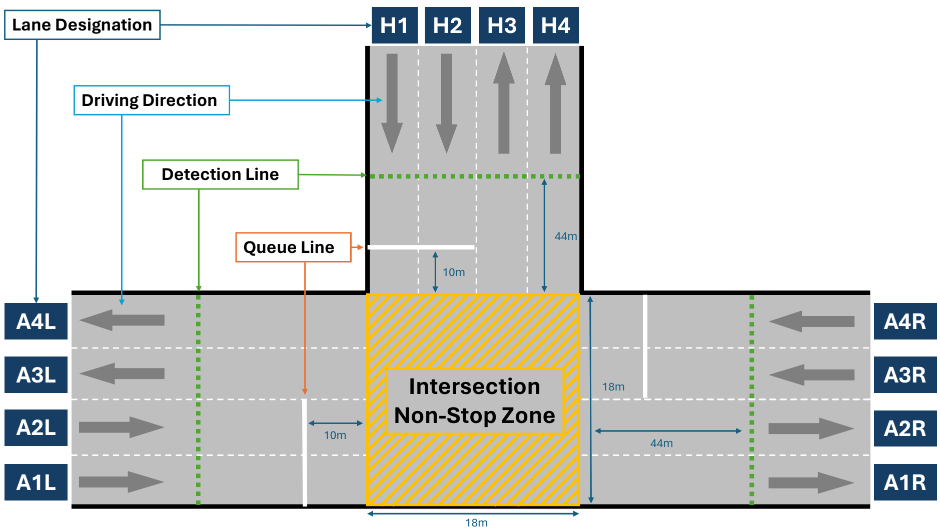

Figure 3.17: Layout of an Apron-Highway Intersection

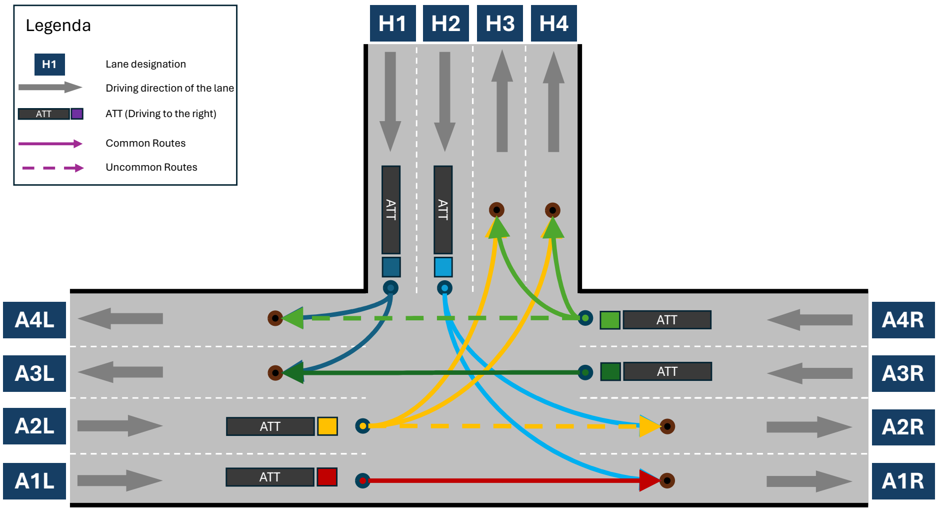

Figure 3.18: Possible routes of ATTs at an Apron-Highway Intersection

3.7.1. Conflict Detection Methods for Intersections

In existing (C)AV intersection literature, there have been two main ways in which conflict and collision detection has been modelled (Gholamhosseinian and Seitz, 2022).

Spatio-Temporal Reservation

In this conflict detection method, an intersection is modeled as a grid of cells. Vehicles that want to cross the intersection, reserve the cells needed to cover the footprint of their intersection crossing action, for the time needed for them to cross the intersection. The aim of the method is to prevent vehicles to be in a common cell simultaneously, and with this prevent collisions between vehicles. A visualisation of this method is shown in Figure 3.19. In this visualisation, both vehicles can be assumed to be are driving straight ahead on a route crossing the intersection. The red cell is then the overlap between their two routes, which is here the source of their conflict.

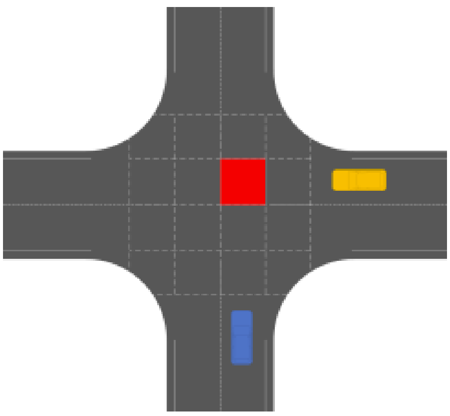

Figure 3.19: Grid Representation of an Intersection (Gholamhosseinian and Seitz, 2022)

Trajectory Planning
In this conflict detection method, the trajectories of vehicles arriving at the intersections are used. This is done by having pre-determined paths for each origin-destination pair for all lanes connected to the intersection. Vehicles arriving at the intersection will check if their trajectory overlaps with that of other vehicles that are queuing at the same intersection. Vehicles without conflicting trajectories are then allowed to cross the intersection simultaneously. A visualisation of this method detecting a conflict in trajectory between two turning vehicles, is shown in Figure 3.20.

The trajectory planning method is chosen to detect intersection conflicts in this study.

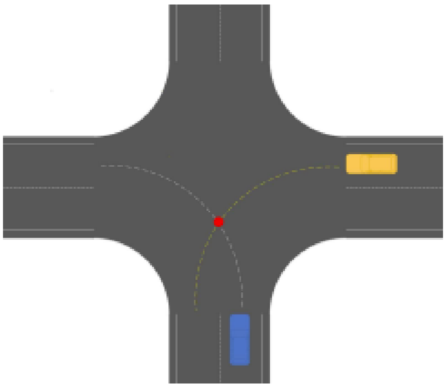

Figure 3.20: Trajectory Representation of an Intersection (Gholamhosseinian and Seitz, 2022)

3.8. ATT-Road Truck Mixed Intersections

At the intersections of the highways and the yard roads, lie intersections on which ATT and road truck traffic mix. In the chosen terminal layout, these are the only real intersections where a mixed traffic situation is supposed to happen during normal operations. It is however always possible that road trucks incidentally drive on the apron and mixing with the ATT traffic at intersections there, during real-life operations. Within the modelled environment these situations can be excluded, and will therefore not be taken into account.

In an RTG terminal environment, these yard-highway intersections are usually characterised by a stop-line for traffic exiting the yard roads, as well as these yard roads being comprised of multiple one-way lanes. Trucks, both manned or automated should come to a complete stop at the stop-line and give way to any traffic driving on the highway. The stop-line is situated between the end of the stack block and the intersection. In addition to the rules involving the stop-line, vehicles driving straight on the highway have priority over vehicles that take a turn from the highway to the yard road. A diagram of this type of yard-highway intersection is visualised in Figure 3.21.

The intersection itself is designated as a non-stop zone, so vehicles should confirm that they are able to finish their turn before entering the intersection, this check is however less strict than the non-stop check of the ATT-only intersections. ATTs should also be able to utilise these yard-highway intersections without the need of the intersection management system or traffic lights.

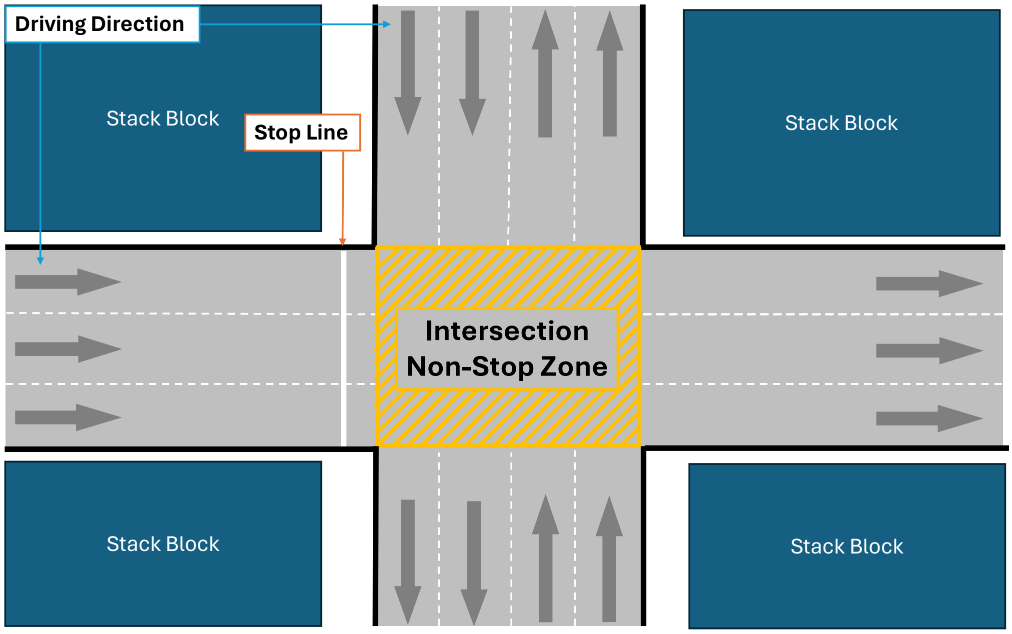

Figure 3.21: Layout of a Yard-Highway Intersection

3.9. Unplanned Situations

By unplanned situations, situations are implied which are not necessarily supposed to happen during normal operations, but which are sufficiently plausible to be possible to happen in a real-life RTG-based terminal system. There are near infinite different possible unplanned situations which the ATT can encounter. As such only a small selection of possible unplanned situations will be further explored in this section, these situations will not be included into the model of the terminal.

3.9.1. Unforeseen Stops

Normally, road trucks should only stop at their destined RTG stack and at the terminal gate, and not anywhere else on the terminal. However it can always occur that a road truck will stop somewhere on the highway or yard road, where it is not supposed to, while an ATT is following it. It is also a possibility that an ATT stops somewhere that it is not supposed to when another ATT or road truck is following it.

ATTs should thus be able to handle unforeseen stops of the vehicle it is following, as well as having a safety routine for making their own unforeseen stoppages known to the vehicles around it.

3.9.2. Congestion

When there are a lot of vehicles that have the same destination and/or want to use the same piece of road, there is the chance of congestion building on that part of the road network. Terminals never want congestion to happen, but at times that there are a lot of road trucks and ATTs deployed at the terminal, this can or even will happen.

ATTs should be able to handle driving on congested highways and yard roads. In essence, congestion and queuing have some overlapping features in stopping and vehicle following behaviour. Congestion is however more unpredictable than queuing, as it can happen in multiple different spots, where as queuing happens at pre-defined spots. Congested intersections may also have vehicles stopped in the middle of a turn on the intersection, if for some reason the non-stop check is not strictly adhered to. Long queuing lines may become the source of congestion if the queue spills over into other roads.

3.9.3. Objects and Unforeseen Vehicles on the Road

It should never happen that there is a stray object blocking a lane in a terminal, but it will inevitably happen at some point or time. It can also happen that another vehicle is standing still or driving in a lane which it should not be in. ATTs should be able to detect that there is something or someone blocking a lane or road, and should be able to handle accordingly by: driving around it, finding a new route or asking a remote driver for assistance.

3.9.4. Road Works

The roads in a terminal require regular maintenance. While this is preformed, this piece of the road will be closed off for vehicles. It should be possible to indicate to the ATT that this route is off-limits and that a detour should be made. However, for safety reasons, the ATT should be able to detect road works as well, as they essentially also act as a kind of road blocking object.

3.10. Conclusions on ATT System Analysis

In the conclusion of this chapter, an answer is formulated to sub-question 2: *How does the internal system and control structure of an ATT function, and how does the ATT interact with other vehicles?*

Autonomous terminal tractors are currently being developed as a driver-less alternative to terminal tractors and a more flexible alternative to AGVs. There are several ATT developers currently in various phases from prototype testing to the first full fleet operations at container terminals. The main distinctive feature of ATTs is that they could be used in a AV-HDV mixed terminal environment. This way ATTs could drive in traffic between human driven road trucks in a RTG based terminal. To perceive other non-ATT vehicles around them, they utilise a set of sensors. The base components of this sensor set are mostly the same across ATT developers, and almost always consist out of at least a LiDAR, Camera and Radar. The signals coming from these sensors are combined in a process called sensor fusion, to combine the strengths and mitigate the weaknesses of each sensor.

ATTs in a container terminal operate within a multi-agent multi-layer control structure. At the strategic control layer there is the terminal operating system (TOS), which is in charge of the planning of container placement and vehicle assignment to jobs. In the layer beneath, the tactical control layer, the fleet management system (FMS) is responsible for the routing of vehicles, facilitating the inter vehicle communication and intersection management. At the lowest layer, the operational control layer, lie the vision and actuation module of each ATT. For this thesis it is assumed that ATTs can not directly communicate with each other, so they follow a decentralised control structure.

ATTs have various interaction points with the other vehicles on the terminal. They have an overlapping part of their operational area with the road trucks, so at any point on the terminal road network within this area overlap, interactions between the two could occur. Everywhere within their operational area, ATTs could have interactions with ATTs. ATTs also have interactions with RTGs and QCs whenever there are containers loaded or unloaded from the trailer of the ATT.

The intersections with which the ATTs interact come in two different forms. There are the ATT-only intersections and the mixed-traffic intersections. The ATT-only intersections are situated on the intersections of the apron and the highways. As these only serve autonomous vehicles, an intersection management system and conflict detection can be used to coordinate ATTs on these intersections. The mixed-traffic intersections are situated on the intersections of highways and yard roads. These feature a stop-line for yard exiting traffic, which has to yield for traffic on the highway. Both road trucks and ATTs use this rule-set and no additional intersection manager or traffic lights at mixed-traffic intersections.

4

Literature Review

In this chapter, a review of the existing relevant ATT, AGV and (C)AV literature is conducted. First, the literature surrounding ATTs and studies specific on intersection strategies concerning ATTs are reviewed. Then, the methods and tools used in prior ATT and (C)AV studies are reviewed. Lastly, studies on intersection strategies for (C)AVs and AGVs are reviewed. By conducting this set of reviews, an answer can be formulated to sub-question 3: *What is currently known in the literature about simulating ATTs/AVs and ATT/(C)AV/AGV intersection strategies?*

4.1. ATTs in mixed traffic container terminals

There is currently not a lot of literature available on ATTs, as they are still quite a recent development (Gerrits, Mes, and Schuur, 2020).
Gerrits and Schuur, 2022 and Gerrits et al., 2019 explain the basics of how one could implement ATTs with regards to intelligent decision making from the vehicle, and how these vehicles could theoretically interact with HDVs and equipment on the terminal. They propose a self-organizing multi-agent system where all ATTs can make their own routing and movement decisions. Gerrits, Mes, and Schuur, 2020 then went further in depth by simulating these ATTs in a mixed-traffic CT environment using the discrete-event simulation tool Siemens Plant Simulation. Here ATTs interacted with road trucks, RTGs and quay cranes. The field-of-view of the ATT has been modeled as one single 180 degree front facing LiDAR, and the ATT is programmed to slow down and/or stop when this sensor detects other vehicles, obstacles or workers. Experimentation with the number of deployed ATTs in the terminal saw higher congestion and ATT waiting times, but also higher QC utilisation rates with increasing numbers of deployed ATTs. The layout of the tested on terminal itself here was quite basic and did not feature any intersections.

4.1.1. Intersection Strategies for ATTs

Most of the available ATT literature has focused on what kind of traffic rules should apply at intersections where road trucks and ATTs mix. Horst, 2019 has found that if priority is given to road trucks, then the dwell times of these road trucks will reduce and subsequently the crowdednes and congestion would be reduced as well. Chen, Xu, and Wang, 2023 proposed to make the priority strategy at junctions dynamic, with priority shifting between road trucks and ATTs, dependant on the amount of road trucks that are present on the terminal. Ng, Ong, and Zhou, 2022 agrees with that, and also proposes that turning and priority policies should depend on the ratio of ATTs to road trucks. Next to that they also propose that at high ATT to road truck ratios, there should be dedicated lanes for ATTs to drive on. Both Chen, Xu, and Wang, 2023 and Ng, Ong, and Zhou, 2022 however note that such dynamic priority strategies have only been tested in simulations, and as such are only more efficient in theory. It is still unknown how road truck drivers would react to such dynamic policies.

4.2. Simulation Methods and Tools

From the aforementioned ATT in mixed-traffic container terminal studies, Gerrits, Mes, and Schuur, 2020, Horst, 2019 and Ng, Ong, and Zhou, 2022 all used discrete event simulation. This follows the trend amongst container terminal simulation studies, where discrete event simulation has been the most popular simulation method amongst published papers (Dragović, Tzannatos, and Park, 2017). A downside of using these discrete event simulation tools to simulate the mixed traffic between ATTs and HDVs, is that the accuracy of the simulation is largely dependant on the accuracy and validity of the model of the HDV. Simulations of AVs have mainly been done trough microscopic traffic simulations, especially when it comes to car-following and lane-changing models. The tools with which these types of simulations are done, often have validated HDVs in their open source library. Next to that, is a more recent development the inclusion of AV sensors and AV-to-AV connectivity within these microscopic simulations (Farah et al., 2023), (Sadid and Antoniou, 2023).

In terms of discrete event simulation tools, has ARENA been the most utilised by container terminal simulations (Dragović, Tzannatos, and Park, 2017) and for ATT in mixed-traffic container terminal simulation studies specifically, Siemens Plant Simulations and PTV Vissim were used (Gerrits, Mes, and Schuur, 2020), (Ng, Ong, and Zhou, 2022). When looking at open-source microscopic traffic simulation tools for AVs which have been used in prior research, the most widely used simulator is CARLA. This simulator allows for the 3D simulation of AVs in traffic scenarios on representations of public roads, with vehicle and object detection via a sensor suite which includes all commonly used sensors by AVs (Carla, 2023). Similar to CARLA, there is SVL Simulator, which also allows for machine learning training within their software (SVL-Simulator, 2023). There are also microscopic traffic simulation packages like SUMO, these could be combined with 3D simulator Gazebo to integrate a more complete sensor sensor suite into it (Garzon and Spalanzani, 2018).

There are also simulators which have been created by some of the developers of ATTs. AI Drivers and Westwell have both developed simulation environments in which scenarios can be created to test their ATTs on terminal layouts, called AISE and Well SIM respectively (AI-Drivers, 2023) (Westwell, 2023). Except from these companies claiming that the simulation software exists, there is very little to find about them, and neither did any prior study use one of these simulators. As these simulators are most likely designed for in-house use by these companies only.

4.3. Intersection Strategies for (Connected) AVs

There have been numerous studies on intersection strategies specific for CAVs. Gholamhosseinian and Seitz, 2022 has reviewed 278 papers on this topic alone. They found that safety was by far the most researched topic for CAV intersections, followed by intersection efficiency. Nearly all studies utilised an optimization based coordination method for the intersection and trajectory planning as a method to check for conflicts at the intersection. There was a larger mix in architecture type between studies, with approximately 50% using a Vehicle-to-Vehicle (V2V) architecture, 40% a Vehicle-to-Infrastructure (V2I) architecture and 10% using both V2V and V2I. For this thesis, only studies using a form of V2I will be included in this section of the review.

Dresner and Stone, 2008 have proposed one of the first CAV intersection strategies with a First Come First Serve (FCFS) policy, using a spatio-temporal reservation grid in order to regulate a collision free vehicle flow on the intersection. They found that this intersection strategy vastly improves the throughput of a fleet of fully autonomous vehicles at the intersection when compared with traffic lights. The improvements are however largely diminished when HDVs make use of the same intersection. To mix the AVs and HDVs at the intersection, they have used a traffic lights which interact with the FCFS system.

Li and Liu, 2020 and Worrawichaipat et al., 2021 both proposed different design ideologies to the FCFS strategy, mainly with respect to the computational time needed by the intersection management system to compute if vehicle combinations are possible on the intersection.

Li and Liu, 2020 have proposed a low computational extension to the non-mixed FCFS strategy, incorporating a set conflict matrix and tested its efficiency against traditional and adaptive traffic lights. This matrix gives an overview of which origin-destination routes at the intersection conflict with each other. The intersection management system then checks using the matrix if approaching CAVs have a conflicts with each others route at the intersection. This intersection strategy is tested to be about as efficient as the original FCFS strategy of Dresner and Stone, 2008, but with a much lower computational burden on the central intersection management system.

Worrawichaipat et al., 2021 have proposed a FCFS strategy with a lower computational burden for the central intersection manager by incorporating a mix of V2V and V2I. Here the driver agents of the CAVs themselves do the path prediction and collision avoidance locally based upon a reservation map they receive from the central intersection agent. They then request access to the intersection from the central intersection agent based upon their predicted path. The central intersection agent here only regulates these reservations. It is tested against a traffic light scenario and the traditional FCFS strategy, and is found to be as approximately as efficient as the latter.

Chouhan and Banda, 2018 and Liu et al., 2019 have both proposed strategies which move away from the FCFS strategy of Dresner and Stone, 2008.

Chouhan and Banda, 2018 have proposed a three step heuristic for the scheduling at non-mixed intersections with a First-Enter-First-Serve strategy, which differs with the FCFS strategy by incorporating the approaching velocity of vehicles and how quickly these vehicles would clear the intersection, into its scheduling decision making process. The proposed First-Enter-First-Serve strategy is however not completely collision free, with the two other steps in the heuristic, a window scheduling and a reservation scheme, covering this weakness in the First-Enter-First-Serve strategy. This strategy is tested to have a higher throughput than the FCFS strategy at high traffic densities.

Liu et al., 2019 have proposed a cooperative scheduling mechanism for CAVs at a non-mixed intersection. This mechanism is not based upon the FCFS strategy of Dresner and Stone, 2008, but uses a different strategy that minimises the average waiting time of CAVs at the intersection. They utilise spatio-temporal reservation to detect conflicts between routes, and a window search method to determine the optimal schedule for vehicle movements on the intersection. This has been tested against traditional and adaptive traffic lights, and shows to have a significantly larger throughput than both.

It is worth noting that all mentioned papers on CAV intersections, have only tested their intersection strategies on a model of just the intersection alone, and these intersections are based upon intersections found on public roads. This does make the outcomes of these studies very accurate on the efficiency of the intersection, but gives little insight in how these intersections would impact a larger road network with multiple of these intersections. Li and Liu, 2020 and Liu et al., 2019 both included recommendations to test their strategy in an actual road network. Another observation is that CAV Intersection studies often take a situation with traditional traffic lights as a base benchmark to test their intersection strategies against, with Dresner and Stone, 2008,Li and Liu, 2020, Worrawichaipat et al., 2021 and Liu et al., 2019 all doing this.

4.4. Intersection Strategies for AGVs

AGVs in container terminals have been the subject of many studies over the last few years. However most research has been in the direction of routing and scheduling strategies, with others also focusing on collision and deadlock prevention (Carlo, Vis, and Roodbergen, 2014). AGVs in container terminals generally do not utilise traditional intersections like those on public roads or RTG based terminals. The seaside of an AGV based terminal has mostly a configuration as is visible in Figure 4.1, which has no highways intersecting on the apron. Because of this, AGV based research is less relevant for this thesis with respect to intersections. However, the way AGVs solve claiming conflicts does draw similarities to how conflicts at ATT-only intersections could be solved as well.

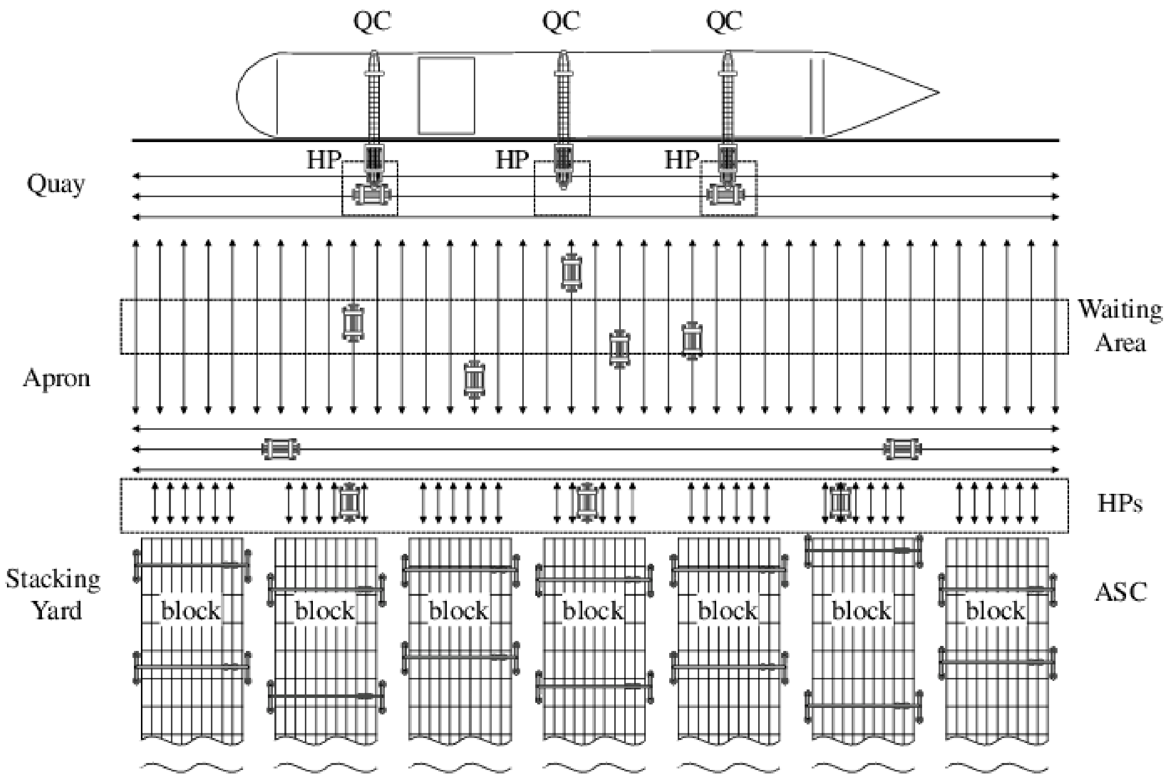

Figure 4.1: Diagram of the Seaside of an AGV Based Terminal (Kim, Choe, and Ryu, 2013)

Similar to CAVs, the FCFS strategy has also been widely used to solve AGV claiming conflicts, and also similar to CAVs, there have been numerous strategies which have been proposed to be better than the FCFS strategy.

(Chan, 2022) has proposed a conflict resolution module using CPLEX and mixed integer programming, to find the optimal conflict resolutions in AGV schedules, both with and without giving weighted priorities to AGVs. The conflict resolution module proved slightly but noticeably more efficient than the FCFS strategy, with respect to QC productivity. Adding the weighted priorities did not have a significant impact.

(Zheng et al., 2022) have proposed an adaptive learning algorithm to generate a optimal policy for dynamic AGV scheduling. They have tested their algorithm against the FCFS strategy and found it gave a significant improvement of QC productivity over the FCFS strategy.

AGVs have also been implemented in industries outside of container terminals, like warehousing and manufacturing. The characteristics bound to the term ”AGV” also vary slightly, dependant on which industry they are operational in. Because of this reason, all non-container terminal applications of AGVs have been left out of scope.

4.5. Conclusions on Literature Review

In the conclusion of this chapter, an answer is formulated to sub-question 3: *What is currently known in the literature about simulating ATTs/AVs and ATT/(C)AV/AGV intersection strategies?*

There have not been many studies on the subject of ATTs, mainly because they are still a recent development. The few available studies have mainly focused either on overall ATT efficiency or traffic rules for mixed traffic intersections. For these mixed traffic intersections, it was found that dynamic traffic rules with priority for either ATTs or road trucks, or ATT-only lanes, dependant on ATT to road truck ratio would lead to the theoretic most efficient intersection strategies in these cases.

In terms of the methods used for ATT simulation studies, these have mainly been conducted using discrete event simulation. This is follows the trend of container terminal simulation studies, of which a significant share also utilised discrete event simulation. AV simulation studies on the other hand, have mainly used microscopic traffic simulations, with tools developed for the use of virtually testing AVs and AV sensors.

In terms of intersection management and strategies, there have been a few studies on this using ATTs, however these have been focused only on the mixed-traffic intersections. There have been numerous studies on CAV-only intersections, here the FCFS strategy has been utilised in each featured study as a benchmark, to which either an amended FCFS strategy or non-FCFS strategy has been tested. All of the featured CAV-intersection studies only utilised a one-intersection layout as a test configuration.

AGV based systems in container terminals usually do not feature the same type of intersections as (A)TT based terminals. The way scheduling conflicts are resolved however, does bear a resemblance to the way intersection conflicts at ATT-only intersection could be handled. In the featured studies of AGV scheduling conflicts, FCFS has also been used as a benchmark to test novel scheduling solutions against.

5 Modelling

In this chapter, all modeled systems within this study are discussed, to give a clear picture what the models are with which the simulation study is conducted. First, the model of the RTG-based container terminal is discussed. This is the highest level model within this study, and all other models are built within this one. Then model of the ATT and model of the ATT controller are discussed more in depth, here the ATT controller model is a part of the ATT model itself. For these, also the verification and validation of the models will be discussed. Lastly, the model of the Intersection Management System (IMS), including all built in intersection strategies are discussed. By discussing how these systems are modelled, an answer can be formulated to sub-question 4: *How can the controller of an ATT be modelled in a microscopic discrete event simulation to be a valid representation of ATTs in real-life?*

5.1. Model of the RTG-based Container Terminal

The TIMESQUARE model of the RTG-based terminal has been developed and validated by Portwise, as a test terminal for new vehicle models for their simulations. It is not necessarily modelled after an existing terminal, but it does share a resemblance to the Hutchinson Laem Chambeng terminal in Thailand and the Kao Ming terminal in Kaoshuing Taiwan. Rather, it is chosen to be as simple and basic of a parallel RTG-based terminal as possible. This way factors which are dependant on terminal layout design will have a minimal role on the performance of the terminal.

5.1.1. Goal and Scope

The goal of the terminal model is to supply an environment in which the ATT model could perform the operations, and have interactions with the infrastructure and other vehicles on the terminal, in as close of a real life representation as possible, with an exception to the RTGs.

Requirements

The model of the terminal should be able to:

1. Facilitate the movements of ATTs and road trucks in a realistic way on the terminal road network.
2. Facilitate the four terminal operations specified in Section 2.3.

Assumptions

Assumptions about the model of the terminal include:

1. There are already a pre-existing TOS and FMS implemented in the terminal model, which are in charge of the order dispatching and route planning of ATTs, RTGs and QCs.
2. The workings and operations of QCs and RTGs are already implemented in the terminal model, and do not require further changes to be able to work with ATTs.
3. All vehicles operating on the terminal keep themselves strictly to the terminal traffic rules.
4. There are no unforeseen situations happening in the terminal.

5. The weather conditions on the terminal are dry and optimal. So no rain, snow, fog, hard wind or puddles.
6. RTGs stay on their initial stack block the entire simulation, and do not move between stack blocks. To compensate for reduced flexibility due to fixed RTG locations, the terminal features more RTGs than would typically be applied.

Inputs
The inputs of the model of the terminal include:

1. A vessel container stowage plan
2. A road truck arrival schedule

These inputs are generated randomly but within realistic boundaries, by the TIMESQUARE simulation environment.

Outputs and KPIs
The possible outputs and KPIs of the model of the terminal include:

1. The average, minimal and maximal road truck turn around time (meaning the time from entering the terminal gate until leaving the gate)
2. Quay crane productivity (in containers serviced per hour)
3. Intersection throughput (in vehicles crossed per hour), of the ATT-only intersections

5.1.2. Infrastructure

The layout of the test terminal features 32 stack blocks, in a parallel 4 X 8 configuration with single-way three-lane yard roads running parallel to the long side of the yard stacks in the same way as is visualised in the terminal system analysis Figure 2.5. There are also five two-way four-lane highways running along the short side of the stack blocks.

At the waterside there is one 1000 m long quay featuring 10 QCs, with a one-way four-lane quay road running under them, and a two-way four-lane highway running parallel to it. At the landside there is a parallel running two-way two-lane highway which ends in the entrance road to the gate. A visualisation of the layout can be found in Figure 5.1.

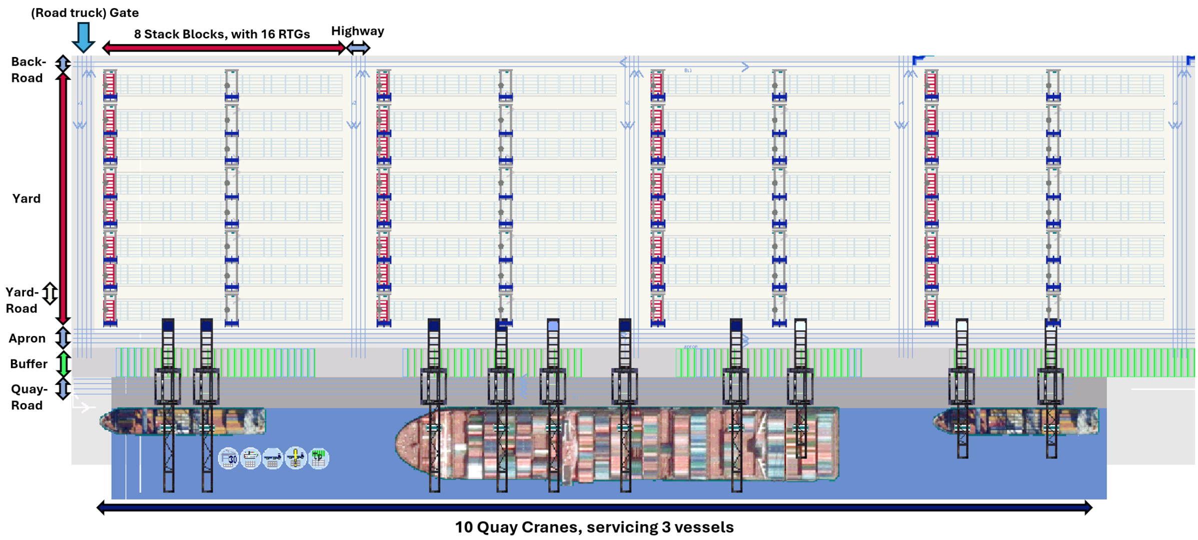

Figure 5.1: Visualisation of the layout of the test terminal

5.1.3. Vehicles

The terminal features 64 RTGs, with two RTGs servicing each stack block. These RTGs stay in their assigned stack block and are thus prohibited from utilising the highways. There are two small vessels and one large vessel moored at the quay, with two QCs servicing a small vessel each and the remaining six QCs servicing the large vessel. The QCs and vessels do not move during the simulation.

External road trucks enter and leave the terminal through the gate. The arrivals follow a pre-determined schedule, where for all cases except noted otherwise, 20 road trucks will arrive at the gate every hour and adhere to an uniform distribution within each hour. The leaving rate of the road trucks is dependant on the dwell time they spend within the terminal, and is subject to change in every experiment. It is assumed that the road truck are not obstructed by any factor outside of the terminal when they are arriving or leaving.
In the current configuration, road trucks utilise the same logic for driving on the terminal and communicating with other vehicles as the ATTs do.

For all simulations, there will be a set number of ATT tractor-trailer combos used in them. These tractor-trailer combos will here-after be referred to as just ATTs, as tractor and trailer will not be de-coupled during the simulation.

5.1.4. Operations

The operations of the model include the loading and unloading of the three moored vessels following a pre-defined stowage plan which is randomised but still realistic across all simulations. It will also include the loading and unloading of road trucks. The sequence of pick-ups and deliveries for road trucks also follows a pre-defined plan, and will also be randomised across simulations. Although housekeeping operations are possible with the model, they are not included in the operations, as they will normally occur when no vessels are moored. Reefer containers are also not included in the model.

5.1.5. Intersections in the Terminal Road Network

The layout of the terminal features 3 ATT-only intersections which are situated on the intersections of the apron and three perpendicular running highways. There are also 12 yard-highway intersections, where road truck and ATT traffic mix. All other crossings of road infrastructure will not be considered intersections in this thesis.

5.2. Model of the ATT

The model of the ATT will be built using the existing model of the TT as a base. This means that there are a lot of functionalities which do not have to be modeled from scratch. The features which should be added to the TT model to transform it into an ATT model are the following:

- A vehicle detection system akin to the sensors on the ATT, able to notice visible vehicles in its sight range and change its speed accordingly to maintain a safe driving distance.
- A rule-based actuation system which takes inputs from the sensors and intersection coordination system, and translates this into actions for the ATT.
- An intersection management system (IMS), which keeps track of all vehicles queuing to utilise the intersection and regulates which vehicle is allowed to take the intersection.

The first two features will be fulfilled by the ATT controller model, which is in its turn a part of the model of the ATT. The model of the ATT controller will be covered in more detail in Section 5.3. The third feature will be fulfilled by the IMS model, which is covered in more detail in Section 5.6.

5.2.1. Goal and Scope

The goal of the ATT model is to give a valid representation of ATTs in real-life within a discrete event simulation environment.

Requirements

The ATT model should be able to:

1. Detect other vehicles on the terminal, how fast the other vehicles are moving, how far the other vehicles are from the ATT and in which direction the other vehicles are moving.

2. Differentiate whether or not a detected vehicle is an ATT or road truck, and use a more precise path for the future movements of the ATTs than for the trajectory of future movements of road trucks.
3. Use the same set of constraints for detecting other vehicles, as the constraints are on the sensors used by real-life ATTs. Mainly detection range, line of sight obscurity and sight angle.
4. Decide when to slow down, stop or continue moving again, dependant on the traffic situation around it.
5. Independently drive to its given destination when a route is given from the FMS.
6. Interact with other equipment and infrastructure on the terminal, in a similar way to how (A)TTs interact with them in real-world terminal operations.
7. Drive on the terminal road network without collisions or deadlocks with other ATTs and road trucks.

Assumptions
Assumptions about the model of the ATT:

1. All functions except vision and actuation are already present within the TT model, and require no large changes in order to be able to be used within the ATT model.
2. The sensors on the ATT will always detect other vehicles and objects correctly.
3. The model of the ATT can already receive and interpret instructions given by the TOS or FMS.
4. The model of the TT, onto which the model of the ATT is based, is a valid representation of a TT in real life, within the TIMESQUARE simulation environment.

Inputs
Only input values with regards to the ATT will be changed for the simulation model. All other unmentioned possible inputs remain unchanged from the simulation model which Portwise normally uses for these types of RTG-based terminals. The needed input values which are ATT specific, have been provided by an ATT developer, these are the following:

1. Deceleration rate (For normal braking and emergency braking)
2. Acceleration rate (In straights and corners)
3. Maximum speed (In straights and corners)

Outputs and KPIs
The possible outputs and KPIs of the ATT Model include:

1. Average ATT cycle time
2. Percentage of ATT drive status:
    - Driving at maximum straight speed
    - Driving at maximum curve speed
    - Driving at a constant speed (which is not the maximum speed)
    - Braking
    - Accelerating
    - Standing still queuing

5.2.2. ATT Fleet Strategy
In a conventional fleet strategy with TTs, each TT is dedicated to a particular QC. In this dedicated assignment, TTs would only accept orders from the QC it is dedicated to. The reason for operating like this is mainly due to the preference of the dock-workers and their unions. For operations with ATTs, this type of dedicated assignment is not necessary. Instead a pooled assignment is utilised. Here all ATTs on the terminal are part of one large vehicle pool, every ATT in the pool can accept orders from every QC.

5.3. Model of the ATT Controller

In Section 3.4, an example was given on how the control structure of an ATT could look like. For the control structure of the model, a multi-layer multi-agent decentralised control structure is chosen. The logic for this controller has been developed from the ground up for this thesis project, but has been inspired by prior (C)AV controller logic developments.

5.3.1. Goal and Scope

The goal of the model of the ATT controller is to give a valid representation of the controllers and logic used in real-life ATTs.

Requirements

The model of the ATT controller should be able to:

1. Measure the distance and trajectories of road trucks detected by the sensors of the ATT.
2. Make decisions about the maximum allowed speed of the ATT, based upon distance and trajectory measurements of road trucks.
3. Make decisions about the maximum allowed speed of the ATT, based upon information about other ATTs given by the FMS.
4. Follow infrastructure based maximum allowed speed rules.
5. Follow infrastructure based priority rules.
6. Arrange intersection queues following the command of the IMS, when approaching an intersection.

Inputs

1. Sensor detection range and viewing angle
2. Sensor perception processing time (for minimum safety distance calculation)
3. Minimum static distance between two vehicles

5.3.2. Main Decision Making Logic

All logic linked to the designed autonomous behaviour, is called from the Vision Cycle. Each ATT controller features its own Vision Cycle, in which all decisions with regard to actuation of that particular ATT are based.

The main logic tree of the Vision Cycle is visualised in a flowchart in Figure 5.2. This includes all methods of the ATT controller, which are within the green border, as well as the methods of the Intersection Management System (IMS), which are within the yellow border. The IMS is in essence its own separate system from the ATT controller in terms of decision making, but in the model it will only be prompted to take a decision when called by the Vision Cycle.

The Vision Cycle is updated every perception time-step, in order to approach the function of the sensor kit on the ATT. As a base value the perception time-step is set to 1 second, this is mainly done to keep simulation times in check. This is different to the real-life perception time-step of 0.1 second which an ATT sensor kit uses normally. One of the test configurations in Section 6.6 looks at the impact of this change, with the results of this impact being documented in Section 7.2.2.

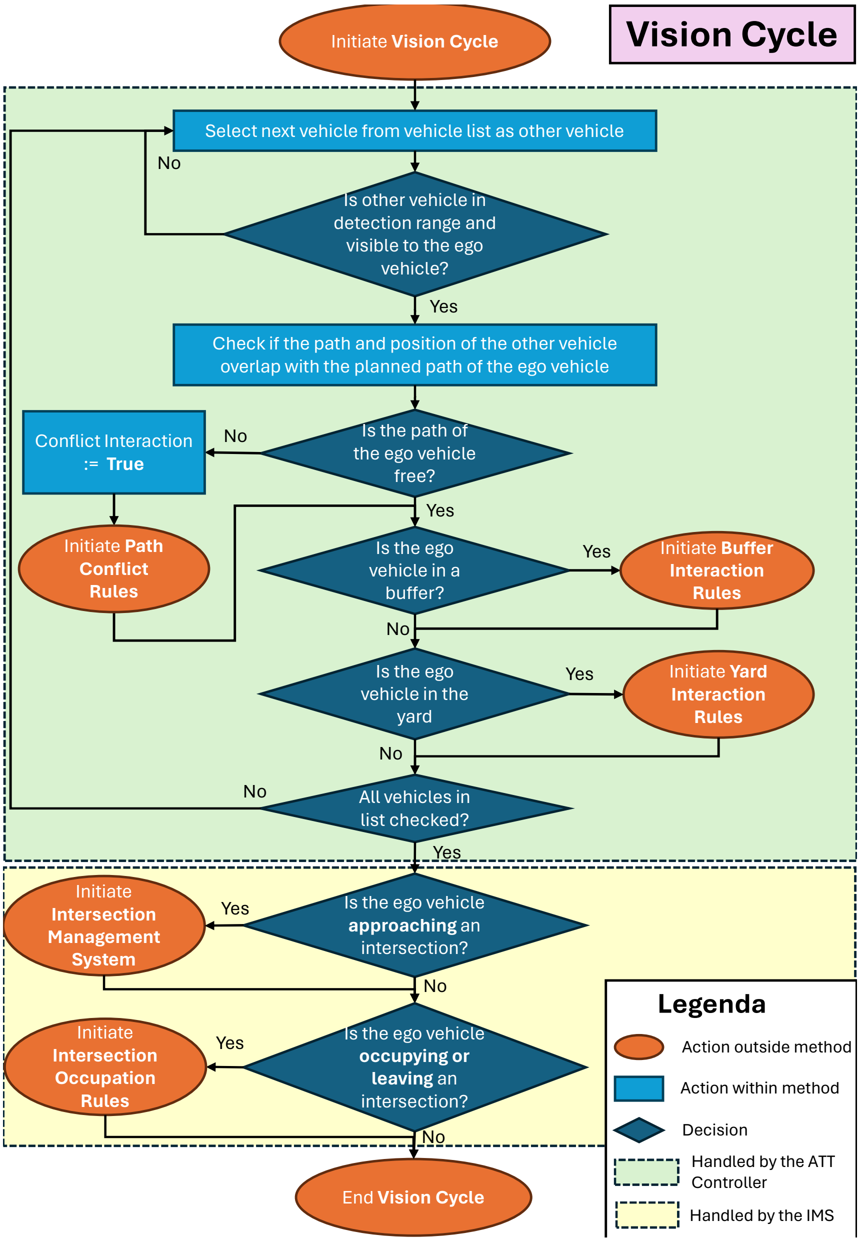

Figure 5.2: Flowchart of the designed ATT controller vision logic

5.3.3. Path Conflict Rules

These rules dictate what the ATT should do when it detects another vehicle on its path. The logic of these rules is visualised in a flowchart in Figure 5.3. As the ATT gets information about the paths of the surrounding ATTs from the FMS, it will also take these into account as long as the other ATT is also moving. There is also a difference made between a conflict on the current path on which the ATT is currently traveling and the next path which has been chosen but has not been entered by the ATT yet. Conflicts on the current path adhere to stricter rules as these could more easily lead to a collision otherwise. In these cases, vehicles will stop to avoid a collision, regardless if they have priority or not. ATTs will always aim to keep the clearance distance between each-other, and will be prompted to brake if there is a path conflict while within clearance distance of the other vehicle.

Conflicts on the next path are resolved dependant on the priority number of both vehicles. The vehicle with priority should potentially slow down a little bit so it could still emergency brake in time if necessary. This action is however dependant on the speed of the other vehicle. The ATT without priority should slow down so it would be at a standstill at the point where the collision would otherwise happen. The priority number of each vehicle is determined by the Priority Checker method.

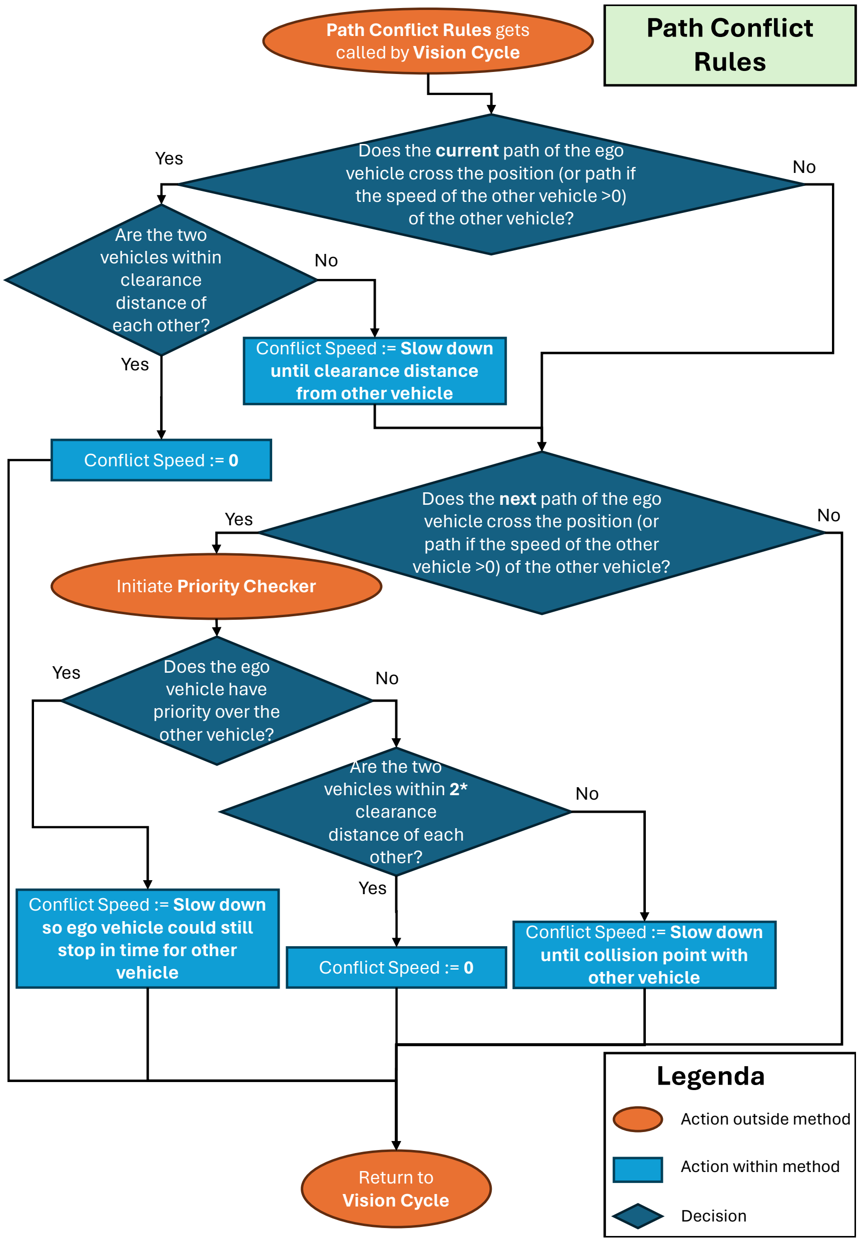

Figure 5.3: Flowchart of the path conflict rules of the ATT

5.3.4. Priority Rules

The logic which decides which vehicle has priority in a conflict situation, is visualised in Figure 5.4. Here the lower the priority-number given to the vehicle, the higher the actual priority of the vehicle is. These priorities are structured in such a way that more defining situations will override priorities of less defining situations. For example, a vehicle which is situated in the buffer but also has the status Idle, will have a priority-number of 99 and not 9.

Some priority defining situations from Figure 5.4 are explained a bit further here:

- **Leaving an intersection:** the trailer of the ATT has completely left the non-stop zone of the intersection and has not yet crossed the detection-line on the exit-lane, while previously occupying the intersection.

- **Pre-turning:** the front of the ATT cabin is less than (2 x total vehicle length + emergency brake distance) away from engaging in a turn.
- **Leaving a buffer, parking or yard-stop-line:** the front of the ATT cabin is no longer in the buffer/parking area or has passed the yard-stop-line, while the trailer of the ATT does still overlap with the area or stop-line.
- **Has just turned:** the front of the ATT cabin is less than 10 m from the end of the previous turn.

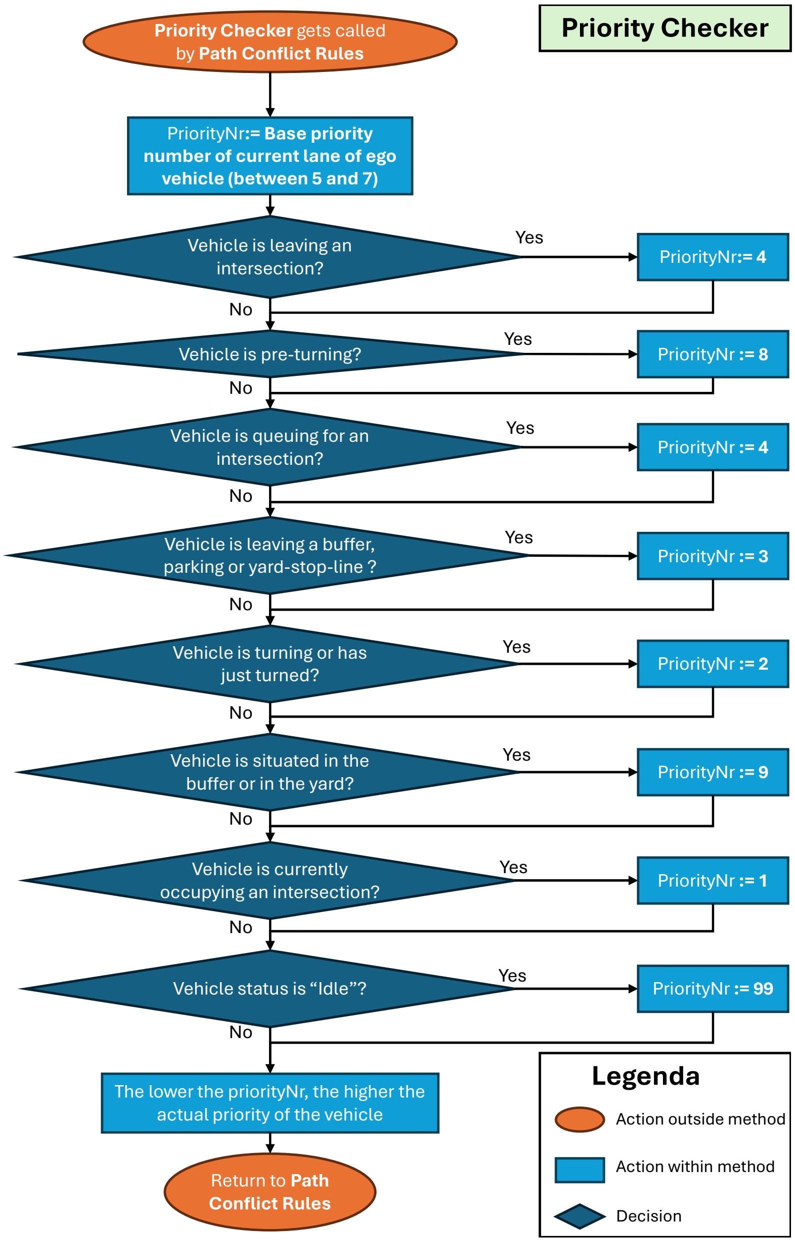

Figure 5.4: Flowchart of the priority rules of the ATT

5.3.5. Buffer Interaction Rules

Buffers function as short term parking spaces for ATTs while they are waiting for a new job or waiting for clearance to approach the QC. The placement of the buffers between the apron and quay road, made the interaction for vehicles entering and exiting the buffer function nearly as several small intersections. As the path conflict rules of the ATT controller can not handle these situations robustly on its own. An additional buffer interaction rule-set was created for ATTs in- or leaving buffers.

When the front of the cabin is still within the buffer area, the ATT has to check if there are no other vehicles right in front or in the direct path of the vehicle, in order to gain clearance to leave the buffer. Dependant on if the ATT in the buffer is going to take a right or left turn out of the buffer, it has to check if there are vehicles approaching from the just left; or from the right and left respectively. It is thus important to note that ATTs coming from the buffer never have priority over vehicles on the highway or quay road. When the ATT is cleared to leave the buffer, it will get the designation leaving buffer as the front of the cabin leaves the buffer area. It will keep this designation as long as the trailer of the ATT still overlaps with the buffer. A flowchart of these rules is visualised in Figure 5.5.

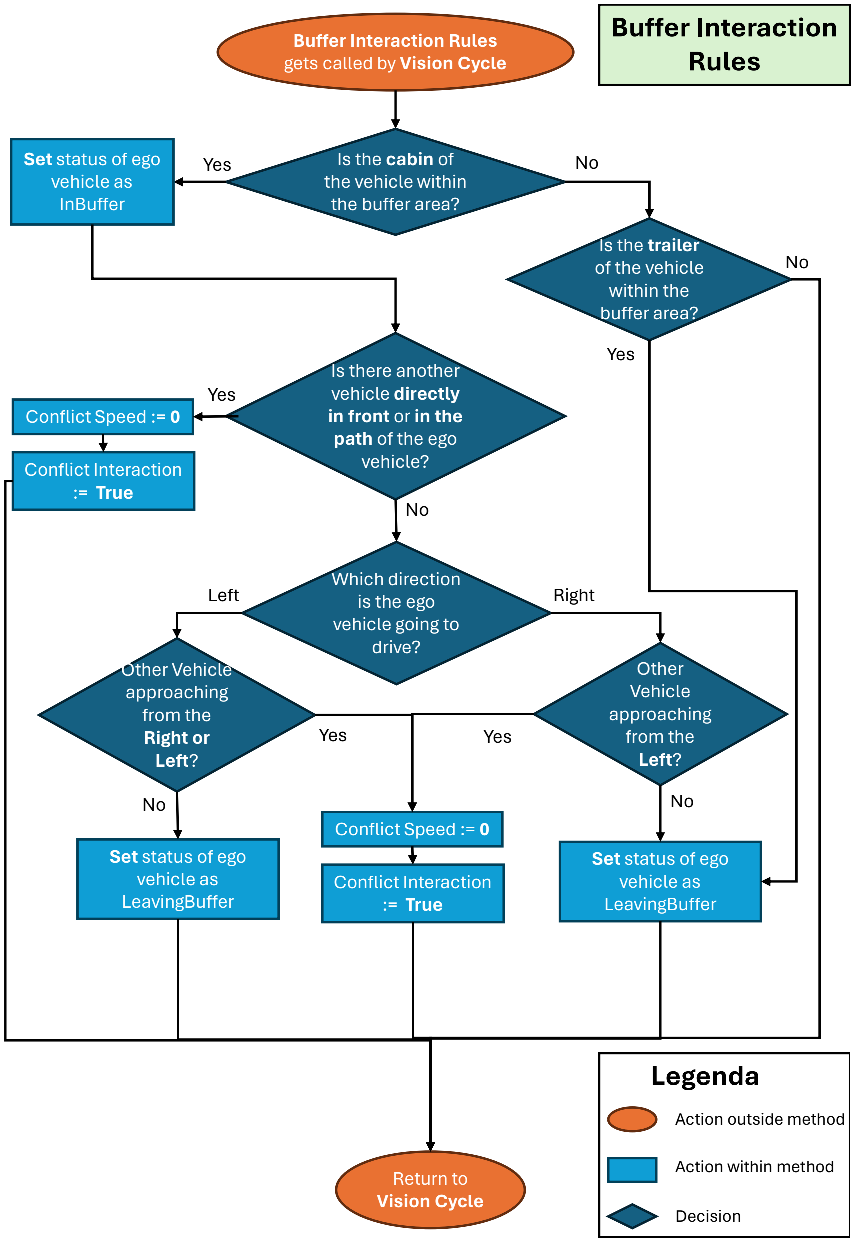

Figure 5.5: Flowchart of the buffer interaction rules of the ATT

5.3.6. Yard Interaction Rules

The yard interaction rules dictate how ATTs should act when they are approaching the end of the yard road and want to enter the yard-highway intersection. The yard-highway intersections feature a stop-line at the end of the yard road, this is visualised in ATT system analysis Figure 3.21. ATTs approaching the stop-line will always come to a complete standstill at the stop-line, before assessing if it can enter the intersection. When the ATT is at the stop-line, it will act in a similar way to ATTs that want to leave the buffer and enter the highway.

When the ATT is approaching the stop-line while driving on the yard road, the controller will instruct to decelerate the vehicle until it has reached the stop-line. When the ATT detects that it is at the stop-line, it will scan the region of the yard-highway intersection and the approaching lanes of the highway to the intersection. Similar to the buffer interaction rules, the ATT has to check if there are no other vehicles right in front or in the direct path of the vehicle. Then, dependant on if the ATT at the stop-line is going turn right or continue forward/turn left, it has to check if there are vehicles approaching from the just left; or from the right and left respectively. When all checks are cleared, the ATT will get the designation leaving yard stop-line and the ATT controller will no longer command the ATT to stand still at the stop-line. A flowchart of these rules is visualised in Figure 5.6.

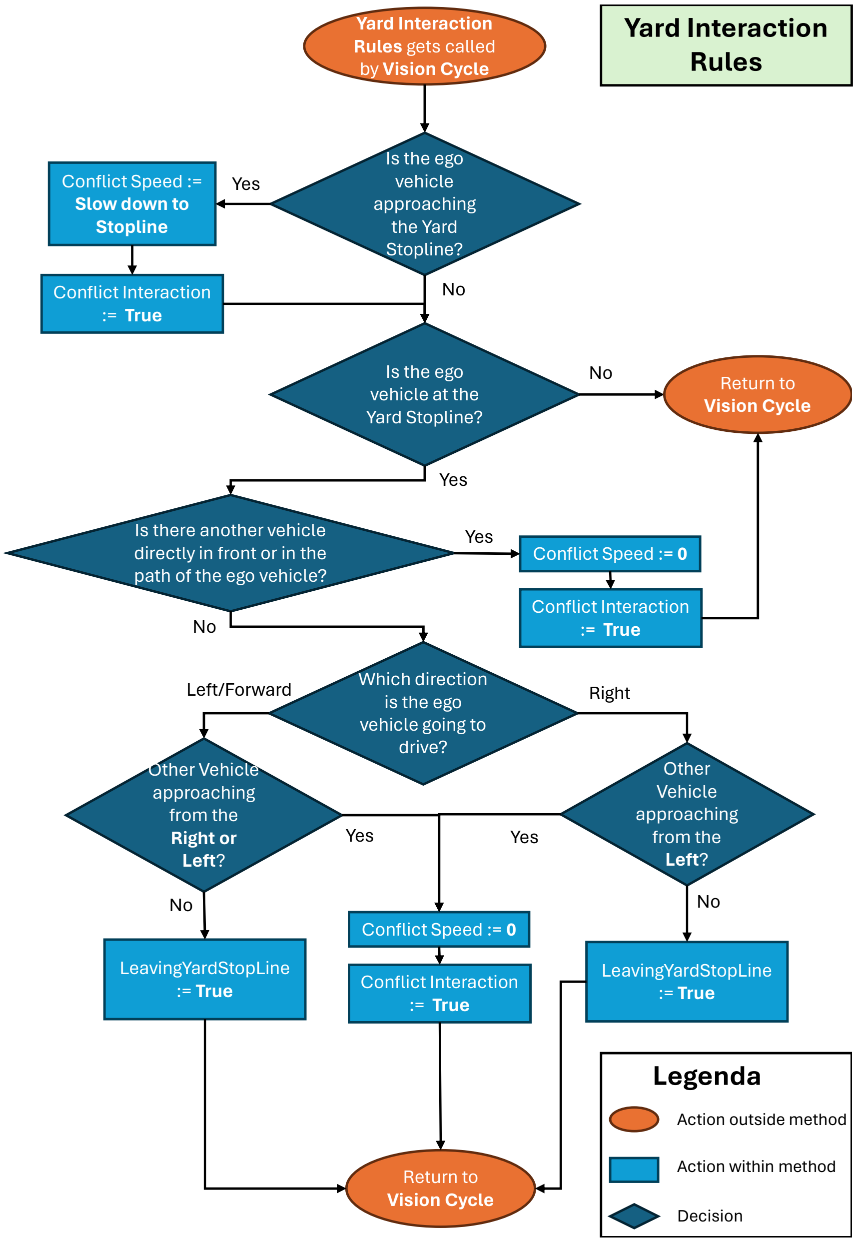

Figure 5.6: Flowchart of the yard interaction rules of the ATT

5.3.7. Equations Used in the ATT Controller Logic

There have only been a few noteworthy equations used within the ATT controller logic. These equations have been used in several different places within the code. All of these have been derived from the minimum safety distance equation, proposed by Shalev-Shwartz, Shammah, and Shashua, 2017. This minimum safety distance equation has been mathematically proven by them to be collision free for the use-case of two vehicles following each other.

All other equations and mathematical functions used throughout the model originated from the MathematicTools from within the TIMESQUARE software library, and will not be discussed further in this thesis.

Minimum Safety Distance

The minimum safety distance signifies the distance (d_{min}) the ego vehicle should keep while following another vehicle, such that the leading vehicle could brake maximally without it leading to a crash, can be defined following Equation (5.1). By including the maximum acceleration rate of the ego vehicle (acc_{ego}) in the equation, it will resemble a worst case scenario where the ego vehicle is still accelerating maximally during the reaction time ($t_{reaction}$) (Shalev-Shwartz, Shammah, and Shashua, 2017), the reaction time is represented by the sensor perception processing time for the ATT. This equation has also been verified by an ATT developer as approaching the same outcomes for the minimum safety distance as the calculations behind their own ATT development in real life.

$$d_{min} = v_{ego} * t_{reaction} + \frac{acc_{ego} * t_{reaction}^2}{2} + \frac{(v_{ego} + acc_{ego} * t_{reaction})^2}{2 * dec_{ego}} - \frac{v_{lead}^2}{2 * dec_{lead}} \tag{5.1}$$

Where v_{ego} is the current speed of the ego vehicle, v_{lead} is the current speed of the leading vehicle, dec_{ego} is the deceleration rate of the ego vehicle and dec_{lead} is the maximum deceleration rate of the leading vehicle. The reason that the maximum deceleration rate is only used for the leading vehicle, is because the ego vehicle has to take into account that the leading vehicle could make an emergency brake manoeuvre, and it should be able to respond to it by not needing to apply the emergency brakes itself.

Equation (5.1) now only works when the leading vehicle and the following vehicle are both driving in the same direction, and in the same lane. The equation can be made more general for all other vehicles interacting with the ego vehicle, by adding $cos(rad_{ego} - rad_{other})$ for the term taking into account the speed and deceleration of the other vehicle. This way, the impact of the movements of the other vehicle are dependant on the driving direction of the other vehicle when compared to the ego vehicle. This is implemented in Equation (5.2).

$$d_{min} = v_{ego} * t_{reaction} + \frac{acc_{ego} * t_{reaction}^2}{2} + \frac{(v_{ego} + acc_{ego} * t_{reaction})^2}{2 * dec_{ego}} - cos(rad_{ego} - rad_{other}) \frac{v_{other}^2}{2 * dec_{other}} \tag{5.2}$$

This adapted equation has been used for all inter-vehicle minimum clearance distance calculations by the Path Conflict Rules. It is also used by the Buffer- and Yard Interaction Rules for the calculation of the detection distance of an approaching vehicle. Meaning that if the distance from the approaching vehicle to the ego vehicle is higher than d_{min}, then the ego vehicle may safely depart from the buffer/yard stop-line.

Stop-Line Braking

There are three situations in which the ATT could be prompted to decelerate and come to a complete stop at an infrastructure based stop-line. This is at the apron-highway queue line, the yard-highway intersection stop-line and the end of the buffer area. Here the minimum safety distance equation of Shalev-Shwartz, Shammah, and Shashua, 2017 has been derived to give the braking distance (d_{stop}) needed to come to a complete stop. This has been done by removing all components of the other vehicle from the equation, and is implemented in Equation 5.3.

$$d_{stop} = (v_{ego} * t_{reaction} + \frac{acc_{ego} * t_{reaction}^2}{2} + \frac{(v_{ego} + acc_{ego} * t_{reaction})^2}{2 * dec_{ego}}) \tag{5.3}$$

5.4. Verification of the ATT Model and ATT Controller Model

The process of verifying that the implemented code matches the designed conceptual logic, has been performed following the techniques of Sargent, 2010. Here structured walkthroughs and traces have been used to test all implemented code within the methods of the simulation model, on their correct implementation and that its output matches what is expected. It is also ensured here that all implemented code is error free.

5.5. Validation of the ATT Model and ATT Controller Model

To test the validity of the created ATT model and ATT controller model, the requirements from 5.2.1 and 5.3.1 are compared to the animations of the ATT model, which are produced by TIMESQUARE. As the ATT controller model is an integral part of the ATT model, both are tested on their validity simultaneously. This validation technique is featured in Sargent, 2010.

5.5.1. Animation based Validation

The graphical representation of the ATT model in TIMESQUARE is done in the visual style of Figure 5.7. It is assumed that this animation is a correct visualisation of the underlying code.

An animation of two simulated hours, covering all basic functionalities of the model has been shown to industry experts from EasyMile and Portwise, in order to collect their feedback on the validity of it. It has also been observed over many real-life hours by the maker of the model, for multiple simulation runs featuring different container plannings, so the ATTs performed different routes in each run. Of all ATT model requirements, there are two which are not met by the current ATT model:
2. *The ATT model should be able to differentiate whether or not a detected vehicle is an ATT or road truck, and use a more precise path for the future movements of the ATTs than for the trajectory of future movements of road trucks*
Though the ATT is able to differentiate between road trucks and ATTs, it does not change its perception based upon that, as both for ATTs and road trucks the precise path of future movements is utilised for the perception. This has been done this way, because the separate perception rules caused for hard to solve situations within earlier iterations of the model.
It is also for this reason that the second requirement of the ATT controller model can not be met, as the trajectory of road trucks is not utilised in the decision making process: 2. *Make decisions about the maximum allowed speed of the ATT, based upon distance and trajectory measurements of road trucks*

7. *The ATT model should be able to drive on the terminal road network without collisions or deadlocks with other ATTs and road trucks*
There are still some instances where the trailer of a turning ATT will collide with an ATT which is driving on the lane next to it. In these cases the other ATT will stop, as it senses a conflict, so the effect on the productivity would be similar to a situation where the other ATT would have stopped for the turning ATT. As such, these interactions have not been changed.

There is also one instance of deadlock between ATTs which still is a reoccurring situation. Here the vehicles are waiting on each other in a circle around a stack block, the animation of this situation is visualised in Figure 5.7. The likeliness of this situation occurring increases with an increase in the number of ATTs in the fleet. The reason that this situation still occurs and is not yet solved in the model, is that the ATT model in its current form can only utilise static routing and pathfinding. This means that the ATT gets assigned a certain path when it is at the start of its route, and it will not stray from this given path. Utilising dynamic routing and pathfinding could solve this issue, but was deemed to time consuming to implement within this thesis project. However to give the best representation of how ATTs would function in real life in this simulation model, a dynamic routing component should be added. ATTs in real-life will also have to option for human tele-operation, which makes it possible to manually alleviate congested situations.

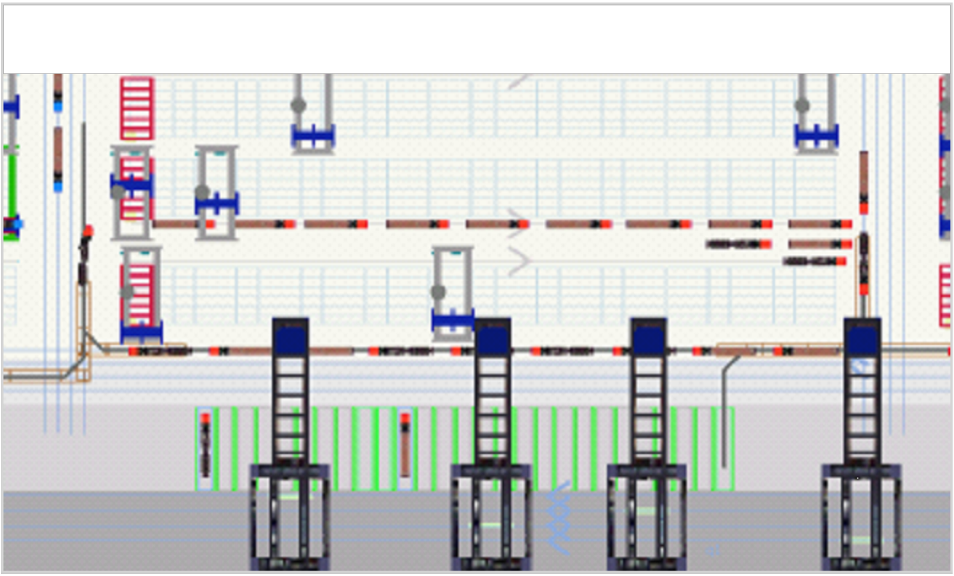

Figure 5.7: ATTs in deadlock in a circle around a stack block

With exception to the second requirement, all other requirements of the ATT controller model have been observed to be met.

5.6. Model of the Intersection Management System

The intersection management system (IMS) is a central control system, which is in charge of coordinating the access of ATTs to ATT-only intersections. The IMS has a different set of rules which it will follow, dependant on which intersection strategy is utilised. The central decision making logic of the IMS is part of the Vision Cycle, but for clarity it is also visualised separately in Figure 5.8.

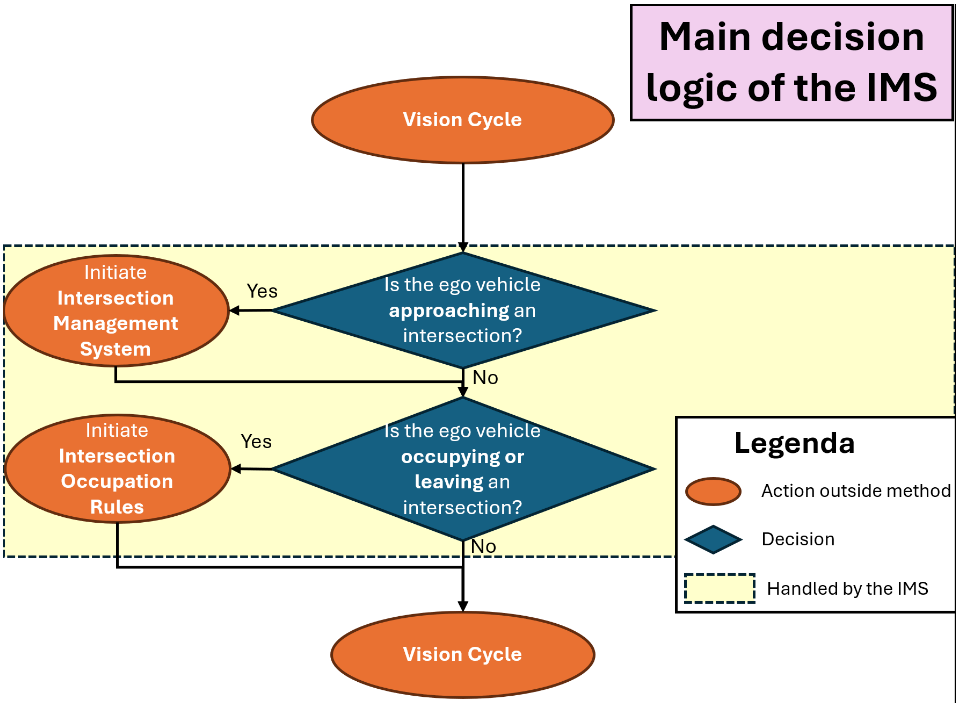

Figure 5.8: Flowchart of the yard interaction rules of the ATT

5.6.1. Goal and Scope

The goal of the model of the IMS is to be a valid representation of how such an IMS could function in a real terminal environment.

Requirements

The model of the IMS should be able to:

1. Coordinate an ATT-only intersection in a collision free manner.
2. Register approaching vehicles in a queue and assign vehicles with a priority in the queue, based upon the logic of the given intersection strategy.
3. Detect and register which route on the intersection a vehicle will take when it is approaching the intersection.
4. Keep unauthorised vehicles from entering the intersection.

5.6.2. Checks for Intersection Occupation

No matter which type of intersection coordination or intersection strategy is used, there are two requirement checks which an ATT must pass before it can be assigned to occupy the intersection.

Firstly, the ATT should have no other vehicle between itself and the actual intersection. Meaning that when it would be assigned as an intersection occupier, it can not be blocked from reaching the intersection by another vehicle in front. This requirement check shall henceforth be referenced as the entry-check

Secondly, the exit path of the ATT should be able to accommodate it in such a way that the ATT can fully exit the intersection. In certain situations there are also vehicles already on the intersection which have the same exit path as the ATT which is requesting entry. In that case, the exit path should be able to accommodate both vehicles. This later requirement is needed in order to deter ATTs from stopping on an intersection and needlessly blocking other vehicles which could have fully utilised the intersection instead. This requirement check shall henceforth be referenced as the exit-check.

5.6.3. During Intersection Occupation

The intersections feature two zones to which the IMS compares the position of the ATT. The inner of these zones is the non-stop zone and the outer is the detection zone. A visualisation of these zones can be found in Figure 3.17. When the vehicle designated as an intersection occupier and is within the non-stop zone, it may ignore other potential conflict interactions it may have. While within the non-stop zone, the ATT is completely dependant on the coordination of the IMS to avoid collisions.

When the ATT has left the non-stop zone but is still within the detection zone of the intersection, it will lose its intersection occupier status and gain the leaving intersection status. This status mainly has impact on the priority number of the vehicle. When the vehicle has also left the detection zone, it loses the leaving intersection status. A flowchart of this decision logic is visualised in Figure 5.9.

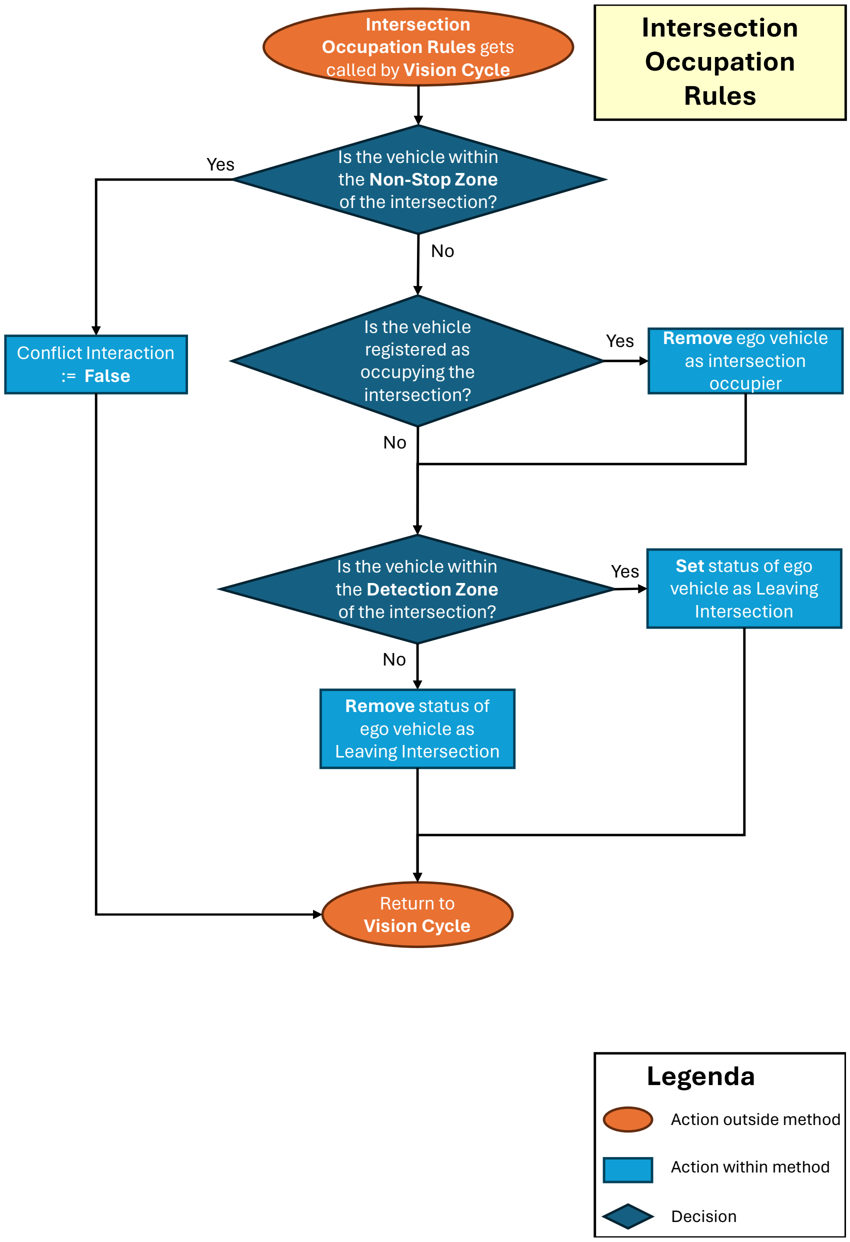

Figure 5.9: Flowchart of the rules when a vehicle is occupying the intersection

5.6.4. One Vehicle at a Time on an Intersection

In this type of intersection coordination, only one vehicle at a time is allowed to occupy the intersection. This means that, no matter if two vehicles could pass each other without conflict on the intersection, the second vehicle will always wait until the first vehicle has completely left the intersection.

This style of coordination has been proposed by multiple ATT developers as a way for the first implementation of their ATT fleets to handle ATT-only intersections. This is because it is a proven safe way to handle these types of intersections.

Strategy: First Eligible First Serve | One-FEFS

In this strategy, vehicles claim the intersection on a First Eligible First Serve (FEFS) basis, if they fulfil the requirements to occupy the intersection, this is done by executing the entry- and exit-checks. This means that the IMS will check if the vehicle first in queue is eligible to occupy the intersection, when the intersection is not occupied. If it is not eligible, it is placed at the back of the queue and the next first vehicle in queue is checked for its eligibility. The logic of this strategy is visualised in Figure 5.10. This

One-vehicle-at-a-time FEFS strategy will be hereafter referred by as the One-FEFS strategy in the text of this thesis.

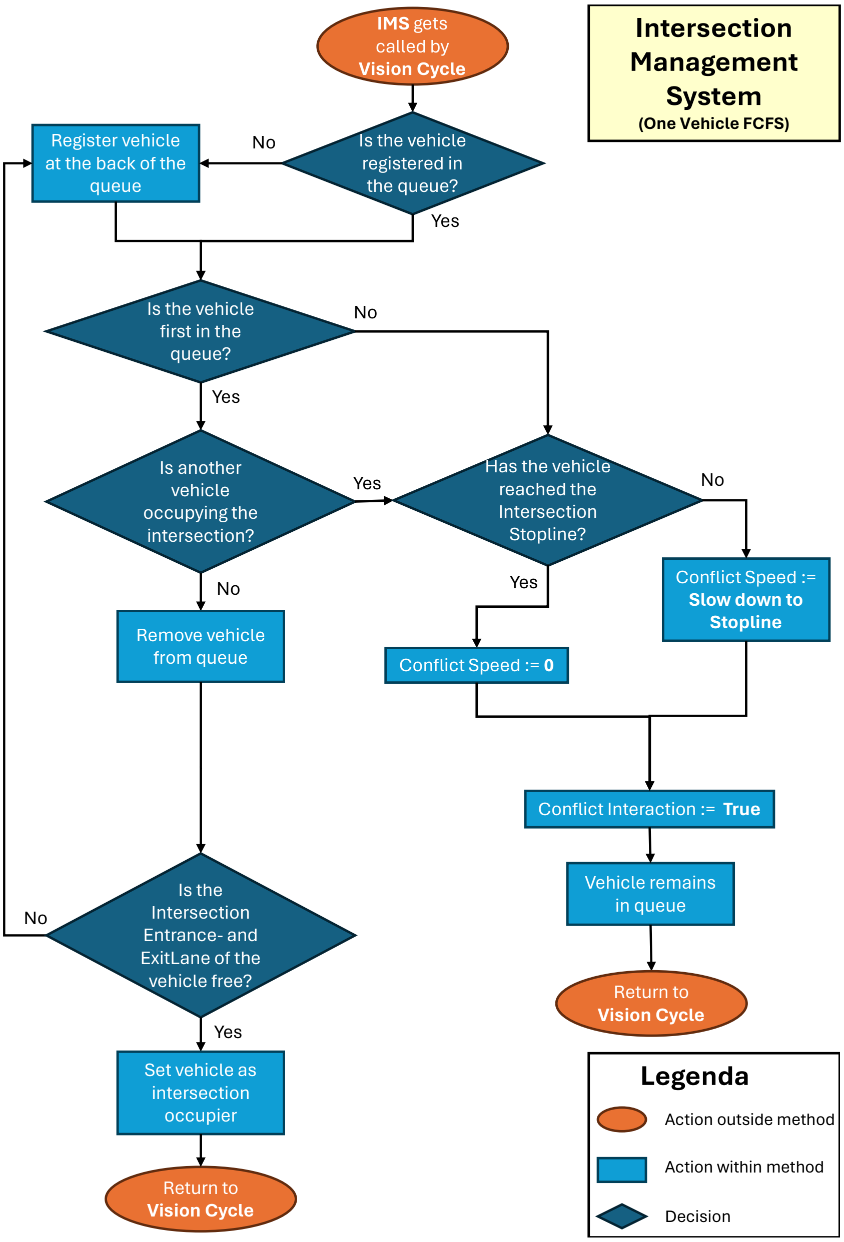

Figure 5.10: Flowchart of the One-FEFS strategy

5.6.5. Conflict Matrix Based Coordination

To designate which turns conflict with each other on the intersection, a conflict matrix is used. Prior research to utilising a conflict matrix for CAV intersections has been done by Li and Liu, 2020. The possible routes for ATTs at an apron intersection, as visualised in Figure 3.18 have been used to create the two conflict matrices of Figure 5.11. Here the first matrix represents the conflicts of ATT routes on the intersection while not taking the sway of the trailer into account, where the second matrix does take trailer sway into account. It is mostly dependant on the width of the lanes as to whether or not trailer sway should be taken into account, and as such it might differ between terminals.

Without Trailer Sway

	A1L -A1R	A2L - A2R	A2L - H3	A2L - H4	A3R - A3L	A4R - A4L	A4R - H3	A4R - H4	H1 - A3L	H1 - A4L	H2 - A1R	H2 - A2R
A1L -A1R	1	0	0	0	0	0	0	0	0	0	2	0
A2L - A2R	0	1	1	1	0	0	0	0	0	0	2	2
A2L - H3	0	1	1	1	2	2	2	0	0	0	2	2
A2L - H4	0	1	1	1	2	2	2	2	0	0	2	2
A3R - A3L	0	0	2	2	1	0	0	0	2	0	2	2
A4R - A4L	0	0	2	2	0	1	1	1	2	2	2	2
A4R - H3	0	0	2	2	0	1	1	1	0	0	0	0
A4R - H4	0	0	0	2	0	1	1	1	0	0	0	0
H1 - A3L	0	0	0	0	2	2	0	0	1	1	0	0
H1 - A4L	0	0	0	0	0	2	0	0	1	1	0	0
H2 - A1R	2	2	2	2	2	2	0	0	0	0	1	1
H2 - A2R	0	2	2	2	2	2	0	0	0	0	1	1

Including Trailer Sway

	A1L -A1R	A2L - A2R	A2L - H3	A2L - H4	A3R - A3L	A4R - A4L	A4R - H3	A4R - H4	H1 - A3L	H1 - A4L	H2 - A1R	H2 - A2R
A1L -A1R	1	2	2	2	0	0	0	0	0	0	2	0
A2L - A2R	2	1	1	1	0	0	0	0	0	0	2	2
A2L - H3	2	1	1	1	2	2	2	2	2	0	2	2
A2L - H4	2	1	1	1	2	2	2	2	0	0	2	2
A3R - A3L	0	0	2	2	1	0	2	2	2	0	2	2
A4R - A4L	0	0	2	2	0	1	1	1	2	2	2	2
A4R - H3	0	0	2	2	2	1	1	1	0	0	0	2
A4R - H4	0	0	2	2	2	1	1	1	0	0	0	0
H1 - A3L	0	0	2	0	2	2	0	0	1	1	2	2
H1 - A4L	0	0	0	0	0	2	0	0	1	1	2	2
H2 - A1R	2	2	2	2	2	2	0	0	2	2	1	1
H2 - A2R	0	2	2	2	2	2	2	0	2	2	1	1

Legenda

0	No Conflict
1	Same Lane
2	Conflict

Figure 5.11: Conflict matrices of the Apron-Highway intersection

In the conflict matrix, 0 represents that there is no conflict between the two routes and that vehicles could utilise both routes simultaneously. 1 represents that these are the same route, as such two vehicles can not take this route at the same time, but they can however take the intersection directly after each-other, with the second vehicle not needing to come to a standstill to let the first vehicle pass the intersection. 2 represents that there is a direct collision causing conflict between the two routes. In this case the second vehicle should wait until the first has completely cleared the intersection before it could safely engage the intersection itself.

It should be noted that the conflict matrix as it is, only takes into account the conflict between two vehicles at the intersection at the same time. If there are already two vehicles occupying the intersection, a third vehicle requesting to enter the intersection should check the conflict matrix for both occupying vehicles.

Using the conflict matrix, an additional requirement check can be performed when a vehicle wants to enter an intersection already occupied by another vehicle. Here a vehicle would be designated as eligible if the matrix returns 0 or 1, and not eligible if the matrix return 2. This requirement check shall henceforth be referenced as the matrix-check. The logic of this matrix-check using the conflict matrix is visualised in Figure 5.12. If the matrix check returns 1, the second vehicle is only eligible to enter the intersection if there is sufficient space for two ATTs on their desired exit-lane, so for this situation the IMS will use this amended exit-check.

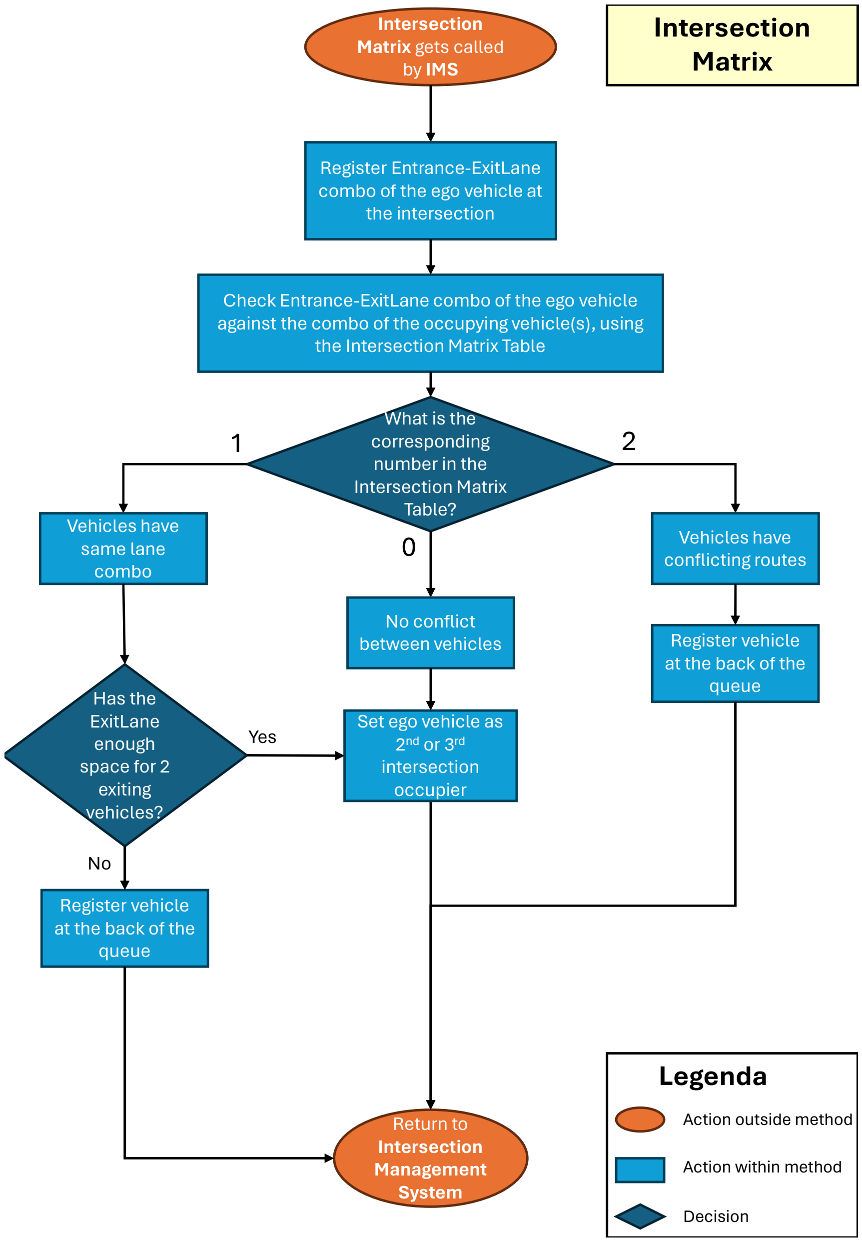

Figure 5.12: Flowchart of the Intersection Matrix eligibility check

5.6.6. Multiple-Vehicles-at-a-Time on an Intersection

The strategies mentioned in this section allow multiple vehicles on the intersection at the same time. To coordinate this to work collision free, the aforementioned conflict matrix is utilised. For all strategies utilising the conflict matrix, the matrix-check applies.

Strategy: First Eligible First Serve | Multi-FEFS

This intersection strategy has been modeled after the one proposed by (Dresner and Stone, 2008), and modified to work with the model of the terminal.

Using this intersection strategy, the vehicle which is first in the queue will enter the intersection, if it fulfils the requirements. Here the entry- and exit-check of Section 5.6.2 are still in effect, and if there is no other occupying vehicle, these are the only requirements for eligibility. If there is already another vehicle occupying the intersection, the extra matrix-check also applies as a requirement for eligibility. The logic of this strategy is visualised in Figure 5.13. This Multiple-Vehicles-at-a-Time FEFS strategy will hereby be hereafter referred by as the Multi-FEFS strategy in the text of this thesis.

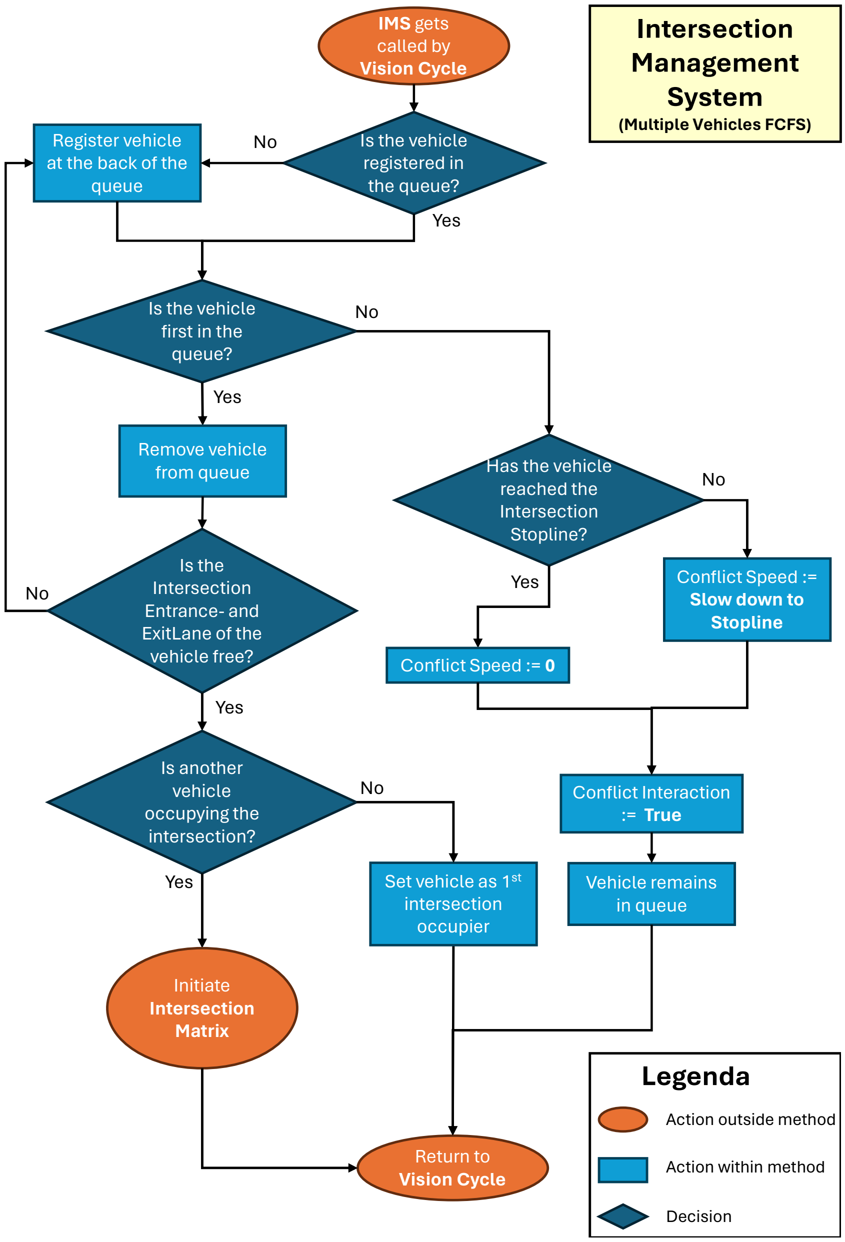

Figure 5.13: Flowchart of the Multi-FEFS strategy

Strategy: QC Destination Priority | QC-Prio

This intersection strategy replaces the ranked queuing system used by the FEFS strategy with a rule which gives priority to eligible vehicles which have a QC as the destination to their route. Vehicles who do not have a QC destination are only allowed to enter the intersection when there are no other eligible vehicles with a QC destination in the queue for the intersection. Here again the entry-, exit- and matrix-checks are used to determine eligibility

The reasoning behind this strategy, is that the overall productivity of the QC is dependant on the minimisation in downtime in between ATTs arriving at the QC for handling. By giving the ATTs which are going to be serviced by the QC priority at intersections, it is expected to increase the time spent productively by the QC.

The logic of this strategy is visualised in Figure 5.14. This QC Destination Priority strategy will hereby be hereafter referred by as the QC-Prio strategy in the text of this thesis.

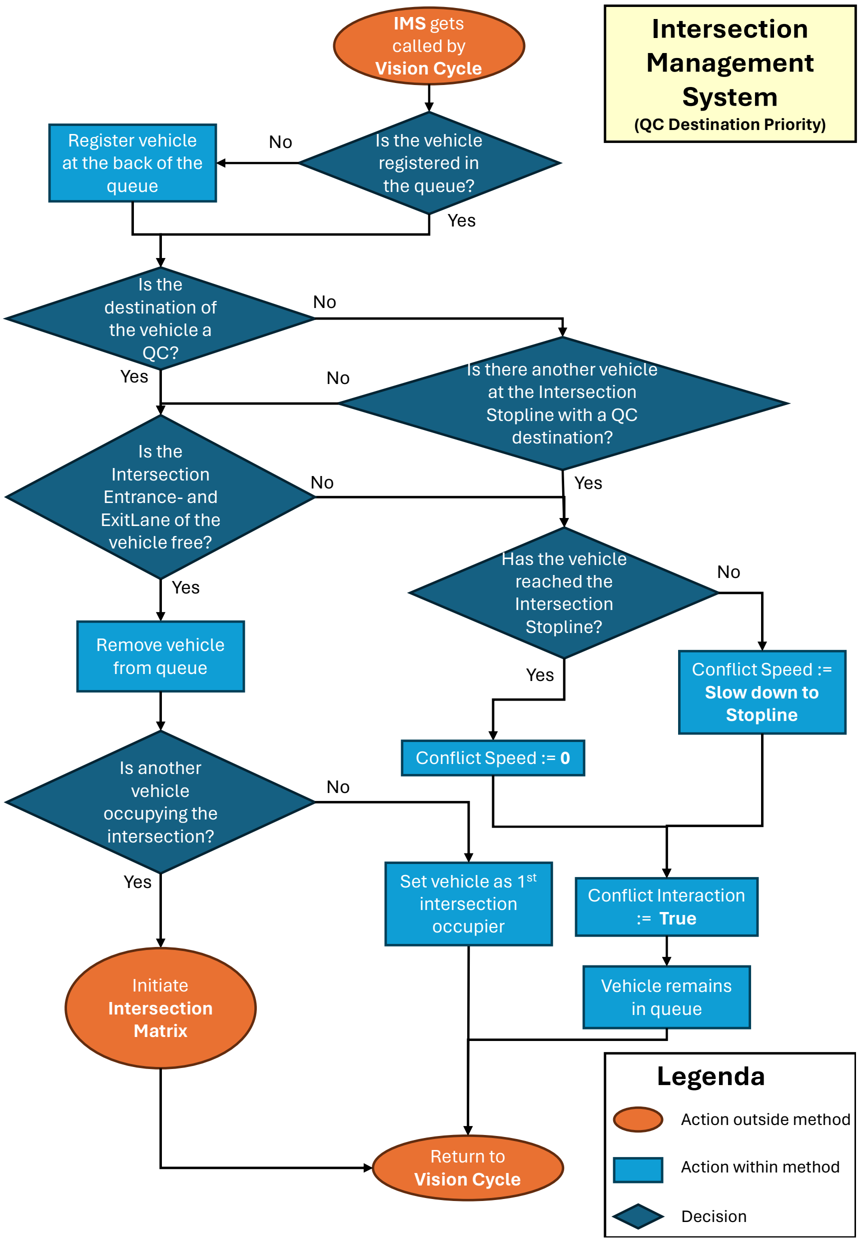

Figure 5.14: Flowchart of the QC-Prio strategy

Strategy: Priority for Delayed ATTs with QC Destination | Delay-Prio
This strategy expands on the QC-Prio, by adding an extra priority filter towards delayed ATTs which have a QC destination. The delay of an ATT is dependant on the elapsed time from the ATT getting their order. Here more delayed vehicles which have a QC destination will have priority over a less delayed vehicle which also has a QC destination. Vehicles with a QC destination will still always have priority over vehicle without it.

The reasoning behind this strategy, is that sometimes QCs have to wait with servicing buffered ATTs, because there is still a delayed ATT carrying the next container somewhere on the terminal. By giving this vehicle priority, it is expected to reduce the time spent waiting by the QC and the buffered ATTs.

The logic of this strategy is visualised in Figure 5.15. This Priority for Delayed ATTs with QC Destination strategy will hereby be hereafter referred by as the Delay-Prio strategy in the text of this thesis.

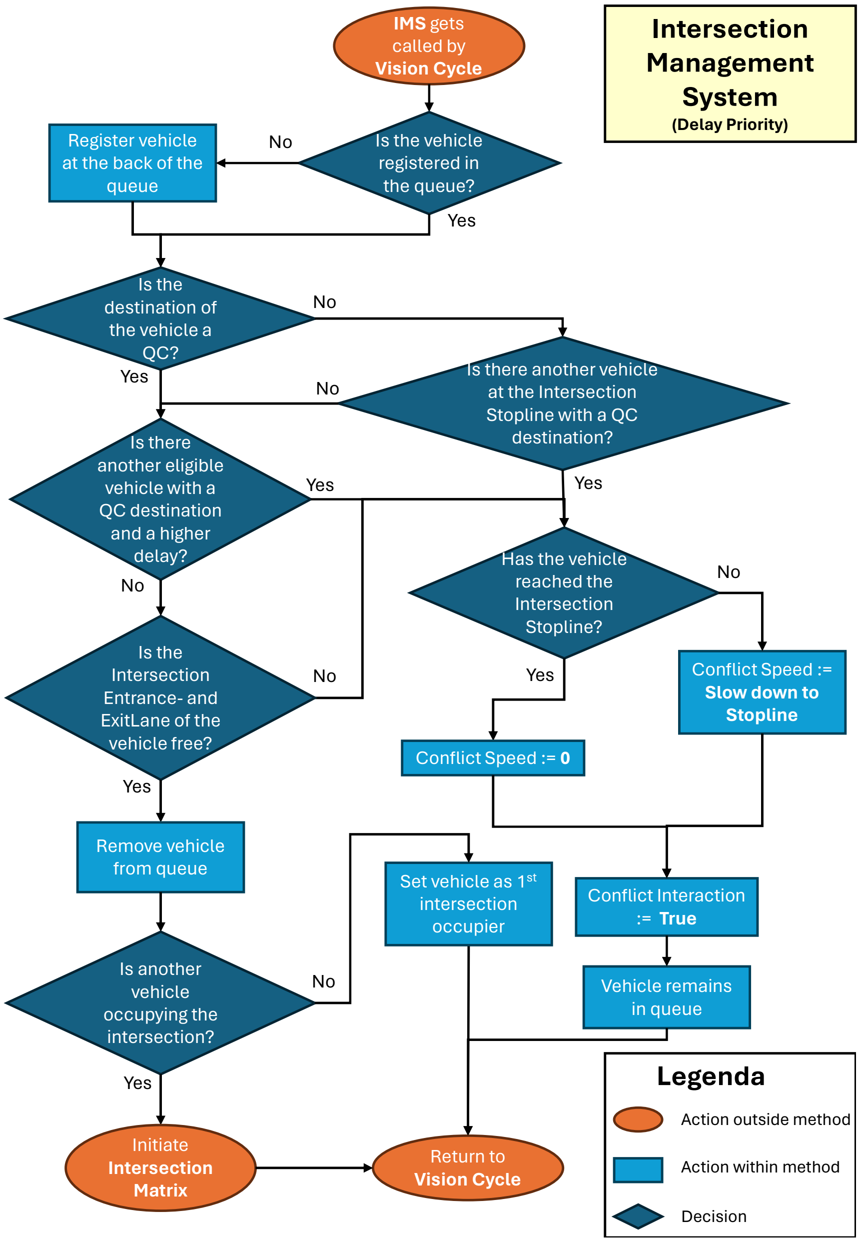

Figure 5.15: Flowchart of the Delay-Prio strategy

5.7. Verification and Validation of the IMS Model

The code implemented for the IMS model and its various strategies has been verified using the same structured walkthroughs and traces technique which has also been used for the verification of the ATT model and ATT controller model.

In terms of validation, the same animation based validation has been utilised as with the ATT model and ATT controller model. Here all requirements stated in 5.6.1 were observed to be working as intended for all proposed intersection strategies. For the intersection strategies which utilised the intersection matrix, it is important to note that requirement 1. *Coordinate an ATT-only intersection in a collision free manner*, is only met while using the intersection matrix which includes trailer sway. While using the intersection matrix without trailer sway, collisions were detected between ATTs.

5.8. Challenges During the Modelling Process

The description of all challenges which appeared during the modelling process can be found in Section B.1, in the Appendix.

5.9. Conclusions on ATT Modeling

In the conclusion of this chapter, an answer is formulated to sub-question 4: *How can the controller of an ATT best be modelled in a microscopic discrete event simulation to be a valid representation of ATTs in real-life?*

There are four systems which were modeled within this study: the RTG-based terminal, the ATT, the ATT controller and the intersection management system.

The model of the RTG-based terminal has been developed and validated by Portwise, as a test terminal for new vehicle models for their simulations. It already has all needed features implemented on it, except for the other modelled systems discussed in this chapter. It follows the layout of a basic parallel RTG-based terminal, featuring 32 stack blocks with 64 stack-bound RTGs, 10 QCs and 20 road trucks arriving at the terminal each hour. The chosen terminal road-layout features 3 ATT-only intersections and 12 yard-highway intersections.

The model of the ATT is based on the existing TT model of Portwise, here a few input values have been changed to reflect the performance of a real-life ATT development. Next to that, the TT model needed some additional features, included in an ATT controller model to be able to function as an ATT model. These features include: a vehicle detection system akin to the sensors on the ATT and a rule-based actuation system which translates inputs from sensors and IMS into actions for the ATT.

The model of the ATT controller has been developed especially for this thesis, to represent how a real-life ATT controller could function. It includes a main decision making logic, which uses the perception of the ATT, the overlap of its path with other vehicles and their paths, and the location of the ATT in relation the infrastructure, to determine its decisions with regard to actuation. This is coordinated by three sets of rules within the ATT controller model: the path conflict-, buffer interaction- and yard interaction rules. All major equations of the controller have been derived from a mathematically proven collision-free minimum safety distance equation.

The model of the IMS has also been developed especially for this thesis, and represents how such a system could function in a real life RTG-based terminal environment. This system coordinates the access of the ATTs to the ATT-only intersections. It does this by utilising an entry-and exit check to determine if an ATT can cross the intersection without stopping. Dependant on the intersection strategy, it also utilises a matrix-check using the conflict matrix, to determine if multiple vehicles can safely enter the intersection together. There have been four intersection strategies included in the IMS: One-Vehicle-at-a-Time FEFS (One-FEFS), Multiple-Vehicles-at-a-Time FEFS (Multi-FEFS), QC Destination Priority (QC-Prio) and Priority for Delayed ATTs with QC Destination (Delay-Prio).

All models made for this thesis have been verified using code walkthroughs and traces, and have been validated through observing the animations produced by the simulation software. There are still some discrepancies between the model of the ATT and ATT controller, and how they would function in real life, which have been noted during the validation process. A large part of this discrepancy could be solved in the future by including dynamic routing and pathfinding in the ATT model.

6

Experimental Plan

In this chapter the experimental plan to be carried out with the simulation model is discussed. First, some introductory information is given about the scenarios, configurations, input parameters and KPIs, which the experiments will use. Then an overview is given of the experiments which will be conducted, these are classified within three categories: Comparative tests between intersection strategies, Parameter influence tests and follow-up tests with the best performing intersection strategy. Lastly, some information is given about the amount of replications, statistical significance, run-length and filtering out of failed replications.

By following the experimental plan in this chapter, experiments can be conducted which will answer sub-question 5: *How do the different intersection strategies impact the operational performance of the ATT model, and how do the ATT performances compare to a model of a human controlled TT?*.

6.1. Test Scenarios

Throughout most experiments, only one main scenario will be tested. There are however also three other scenarios which will be tested as well.

The main scenario is one of a peak-load on the terminal, where containers are simultaneously discharged and loaded on 3 moored vessels, which is the maximum berth occupancy of the terminal. This ensures that there are always jobs available for the horizontal transport vehicles. At the same time, 20 road trucks will arrive each hour through the gate onto the terminal. These will also have a mix of pick-up and drop-off jobs for containers on the terminal.

There are three other scenarios which will be tested in the follow-up tests, the first one is an off-peak-load scenario. Here only half of the QCs and ATTs on the terminal will be active, to simulate the terminal when it is less busy. There will however still be the same amount of ATTs per QC when comparing the peak-load and off-peak-load scenarios. The other two, are scenarios where the road trucks will have an arrival rate of 50 and 100 vehicles per hour. These will also feature a mix of pick-up and drop-off jobs.

6.2. Configurations

Unless indicated otherwise, the configuration parameters for the terminal stated in Table 6.1 and the parameters for the (A)TTs stated in Table 6.2 and Table 6.3, are used as a base for all experiments.

Input Parameter	Value	Unit
# of Stack Blocks	32	-
# of RTGs	64	-
# of QCs	10 (peak) & 5 (off-peak)	-
# of ATT-only Intersections	3	-
# of Yard-Highway Intersections	12	-
Quay Length	1000	m
Terminal Depth	300	m

Table 6.1: Default terminal configuration parameters

There are two sets of input parameters for the ATT model. The first set is specific for ATTs and the values for these have been provided by an ATT developer, the other set is more for TTs in general and has been provided by Portwise. The values and parameters for these sets can be seen in Table 6.2 and Table 6.3 respectively.

Input Parameter	Value	Unit
Max. Straight Speed	6.945	m/s
Max. Speed in Turns	1.897	m/s
Acceleration Rate	1	m/s^2
Deceleration Rate	0.8	m/s^2
Emergency Deceleration Rate	2.8	m/s^2
Emergency Distance Trigger	9	m
Signal Response/Reaction Time	0.8	s
Detection Range	100	m
Viewing Angle	6.2	Radians

Table 6.2: Default ATT specific input parameters

Input Parameter	Value	Unit
Length Tractor	5	m
Width Tractor/Trailer	3	m
Length Trailer	14	m
Turning Radius	6	m

Table 6.3: Default general TT input parameters

The intersection strategies which are discussed within this chapter, are applicable to the ATT-only intersections between the apron and the highway. These strategies are:

- One-FEFS (Section 5.6.4)
- Multi-FEFS (Section 5.6.6)
- QC-Prio (Section 5.6.6)
- Delay-Prio (Section 5.6.6)

All other intersections on the terminal will utilise the same rule-set as is discussed in 3.8 for every scenario and configuration.

To ensure that the bottleneck of the terminal lies with either the horizontal transport vehicles or the QCs, two RTGs are assigned permanently to each stack block. This way, there is no waiting time for the ATTs on RTGs that are moving between stack blocks.

6.3. KPIs

In Sections 5.1 and 5.2, several KPIs were discussed which were able to be measured within the simulation model. Here the three most relevant KPIs for this study will be discussed.

6.3.1. QC Productivity

QC productivity is the chosen KPI to measure the overall productivity of the terminal with, as this is an widely used industry standard for the measurement of the productivity of container terminals. For this study, it will be measured in containers per hour. For the resulting value of this KPI for one replication, the average productivity of all QCs and of all hours of the simulation is taken. Then the average is taken for all replications featuring the same configuration to give a final resulting value.

6.3.2. Intersection Throughput

Intersection throughput is the chosen KPI to measure the efficiency of the ATT-only intersections. It will be measured in the total amount of vehicles entering the intersection within one replication. The three ATT-only intersections each log this KPI separately, and the resulting value is the sum of these three logged values. It is important to note, that due to the way this measurement is logged within the simulation model, no intersection throughput is logged in the non-autonomous TT configuration.

It is expected that there is a positive relation between the intersection throughput and the QC productivity, as the ATT-only intersections are assumed to be the bottlenecks in the terminal system.

6.3.3. Percentage of ATT Drive Status, Standing Still Queuing

The percentage of the ATT drive status standing still queuing, gives an indication of the amount of time an ATT spends in a queue for an intersection. This KPI also tracks the amount of time spent queuing in the yard road for RTG servicing. So the resulting metric is a combination of these two queuing times. It is assumed that the queuing time for RTG servicing does not change significantly between tests with differing intersection strategies, as the rest of the terminal configuration remains unchanged and the RTGs are configured to be as little of a bottleneck as possible within the terminal.

It is expected that there is a negative relation between intersection throughput and percentage of the ATT drive status standing still queuing.

6.4. Benchmark Tests with Non-Autonomous TT Model

The standard TT model from the TIMESQUARE library is used to set a benchmark for the ATT models. In contrary to the ATT models, the TT model uses dedicated assignment of TTs and QCs, so a certain group of TTs will always service the same QC.

The TT model uses some different parameter values when compared to the ATT model, these values are the standard ones from the TIMESQUARE TT model. These values can be seen in Table 6.4.

Input Parameter	**Value**	**Unit**
Max. Straight Speed	8.4	m/s
Max. Speed in Turns	4.16	m/s
Acceleration Rate Empty	0.5	m/s^2
Acceleration Rate Full	0.3	m/s^2
Deceleration Rate Empty	0.6	m/s^2
Deceleration Rate Full	0.4	m/s^2
Driver Response/Reaction Time	1	s

Table 6.4: Input parameters for the TT benchmark model

6.5. Comparative Tests Between Intersection Strategies

A set of comparative tests is run with all previously discussed intersection strategies from Section 5.6. These tests are performed to measure the influence of each intersection strategy on the productivity of the terminal. The intersection strategies which utilise the conflict matrix, will utilise the one including trailer sway for all tests. These comparative tests will be tested using both the peak-load as the off-peak-load scenarios.

6.5.1. Peak-Load Scenario

For the peak-load scenario, all intersection strategies will be tested with fleets of 40, 50 and 60 ATTs, in order to see the effect of the strategy on both low and high vehicle densities. For all fleet sizes, there will also be a benchmark test conducted with the non-autonomous TT model, which is covered in more detail in Section 6.4. All test configurations for these peak-load comparative tests, are listed in Table 6.5.

Intersection Strategy	(A)TT Fleet Size		
One-Vehicle-at-a-Time FEFS	40	50	60
Multiple-Vehicles-at-a-Time FEFS	40	50	60
QC Destination Priority	40	50	60
Priority for Delayed ATTs with QC Destination	40	50	60
Non-Automated TT (Benchmark)	40	50	60

Table 6.5: Configurations for peak-load comparative tests of intersection strategies

6.5.2. Off-Peak-Load Scenario

In the off-peak-load scenario, only half of all QCs are active, which are 5 in this case. As a result, there will also be less (A)TTs active on the terminal when compared to the peak-load scenario, to match this decrease in QC demand, though the amount of (A)TTs per QC remain the same. All test configurations for these off-peak-load comparative tests, are listed in Table 6.6.

Intersection Strategy	(A)TT Fleet Size		
One-Vehicle-at-a-Time FEFS	20	25	30
Multiple-Vehicles-at-a-Time FEFS	20	25	30
QC Destination Priority	20	25	30
Priority for Delayed ATTs with QC Destination	20	25	30
Non-Automated TT (Benchmark)	20	25	30

Table 6.6: Configurations for off-peak-load comparative tests of intersection strategies

6.6. Parameter Influence Tests

There are two parameters which will be tested separately, to gauge their independent influence on the terminal productivity. These are the maximum speed all ATTs are allowed to drive on the terminal and the time-step used by the perception system of the ATT. The values at which the parameters are tested, are listed in Table 6.7, and the parameters are given further explanation in the following subsections. All parameters will be tested one factor at a time, with means that only one parameter will be changed per test when compared to the base case.

Configuration Parameter	Base Case Value	Additional Test Values	
Maximum Speed for ATTs	6.945 m/s (25 km/h)	5.556 m/s (20 km/h)	8.333 m/s (30 km/h)
Perception Time-Step ATTs	1 second	0.1 second	

Table 6.7: Configuration parameters for the parameter influence tests

6.6.1. Maximum Speed for ATTs

For the maximum speed tests, only the One-FEFS intersection strategy is used, for a configuration with a fleet of 40 ATTs.
The maximum speed at which the ATTs are allowed to drive on the terminal, is generally a specification determined by the terminal operator. As a base value for this, 6.945 m/s (25 km/h) has been used, as ATT developers expect this to be the maximum speed at which their vehicles will be allowed to operate. To test the effect of loosening and tightening of this constraint, the base case of 6.945 m/s maximum speed is tested against a case with a maximum speed of 5.556 m/s (20 km/h) and a case

with a maximum speed of 8.333 m/s (30 km/h). It is expected that a higher maximum speed will also result in a higher QC productivity and a higher intersection throughput.

6.6.2. Perception Time-Step

For the perception time-step tests, all featured intersection strategies are used, for a configuration with a fleet of 40 ATTs. Additionally, the Multi-FEFS strategy is used with a fleet of 50 ATTs as well.
The perception refresh-rate of the sensors of ATTs in real-life is 0.1 seconds. During development of the ATT model, it was noticed that the implementation of such a small time-step in the simulation model results in very long simulation times. Because of this, a perception time-step of 1 second was chosen for all simulation tests, and the ATT model was adapted to be able to handle both time-steps. However, the ATT model now needed to account for this change in perception, by taking the 0.9 seconds of added time interval as an extra safety margin. The model with the 1 second perception time-step is thus expected to have a slightly lower productivity than the model with the 0.1 second perception time-step. To measure this difference the base case of a 1 second perception time-step of each intersection strategy is tested against the same configuration with a 0.1 second perception time-step.

6.7. Follow-up Tests with the Best Performing Intersection Strategy

To limit the amount of experiments which needed to be performed, some configurations will only be tested using the best performing intersection strategy, in terms of QC productivity. These will also only be tested for the 50 ATT fleet configuration, under the peak-load scenario. The parameters which will be tested in these configurations are the amount of road trucks per hour entering the terminal, and whether or not the utilised conflict matrix takes trailer sway into account. The values at which the parameters are tested, are listed in Table 6.8, and the parameters are given further explanation in the following subsections. Here all parameters will also be tested one factor at a time.

Scenario/Parameter	Base Case Value	Additional Test Values	
Arrival rate of Road Trucks	20 per hour	50 per hour	100 per hour
Conflict Matrix	With Trailer Sway	Without Trailer Sway	

Table 6.8: Configuration parameters for the best performing intersection strategy

6.7.1. Road Truck Arrival Rate

All previously conducted tests utilised an arrival rate of 20 road trucks per hour to the terminal. This is a very low number for a terminal during normal operations, but was chosen for the sake of simulation speed. To test what what the impact might be of more realistic road truck arrival rates on the terminal productivity, tests are conducted as well with an arrival rate of 50 and 100 trucks per hour.

6.7.2. Conflict Matrix With or Without Trailer Sway

The conflict matrix which includes trailer sway is used as the base case, and all strategies are be tested using this one. The conflict matrix which does not take trailer sway into account will be used to test the theoretical most efficient intersection strategy in a configuration where trailer sway could be neglected. It is expected that ignoring trailer sway would increase the QC productivity and intersection throughput. This does mean that the ATTs will ignore their physically overlapping trailers at the intersection, within the simulation model.

6.8. Replications and Run-length

6.8.1. Amount of Replications

There is no fixed amount of replications which needs to be run for each configuration, rather the number of replications is dependant on the confidence interval of the results of the experiments. A Student's t-distribution with a significance level of 95% is used to calculate the confidence interval for result values of the QC productivity and the intersection throughput.

For the confidence interval of the QC productivity, a deviation of 0.5 containers per hour from the mean is taken as a target value, as this has been used as a target value by Portwise in similar studies. When the confidence interval is above this value, replications are added to try and approach this value. In the case that the standard deviation of the results is so high that adding more replications barely impacts the confidence interval, no more replications are added, as long as the deviation does not exceed 1 container per hour.

This is mainly applicable to the configurations where a lot of replications have failed. For these experiments additional replications will be generated in order to compensate for the failed ones. This will however result in different amounts of replications across the different experiments.

6.8.2. Statistical Significance

To asses whether or not the difference between the results of two configurations is statistically significant, the confidence interval of the one configuration result is compared to the mean result of the other configuration, and vice versa. If in both instances, there is no overlap between the mean of the one and the confidence interval of the other, only then it may be concluded that the difference between both results is statistically significant (Davies and Crombie, 2009). This follows the same principle as the two tailed Student's t-test, which has also been performed between all relevant sets of test results. The resulting P-value from the Student's t-test are featured in Appendix Figure B.3 to Figure B.25, with P-values under 0.05 representing a statistically significant difference.

6.8.3. Run-length

Each run has a length of 8 in-simulation hours, with the first hour being used as a start-up hour where no data is logged for the experiment. As such is the effective run-length of each experiment 7 in-simulation hours.

6.8.4. Filtering out Failed Replications

Not all executed simulation runs will be included in the results of the experiments, as some runs will fail at a certain point. To filter out these runs, the following criterion is used: if the productivity of one or more QCs is equal to 0 from a certain moment until the end of the run, this run is deemed as failed. This indicates that either the code handling the ATT-QC interaction has crashed or the ATTs are standing somewhere in a deadlock. Both are known problematic situations which have been observed to occur sometimes within the simulation model. These situations are not able to occur without stopping the flow of vehicles to one or more QCs and as such, they are easily identifiable.

All of these failed replications will be excluded from the results. In the results there will be noted how many replications have been successful and how many have failed for each experiment.

7

Results

In this chapter, the results of the experiments detailed in the previous chapter, are presented and discussed. Through the analysis of these results, an answer can be formulated for sub-question 5:*How do the different intersection strategies impact the operational performance of the ATT model, and how do the ATT performances compare to a model of a human controlled TT?*

In this chapter only the averages of the results of all replications of a configuration will be used. The separate result data for each replication will be provided by the author on request from the reader.

7.1. Comparative Tests Between Intersection Strategies

In this section, the results of experiments conducted with all proposed intersection strategies are compared to each other and to the result of the non-autonomous model. This is done for both eth peak-load and off-peak-load scenarios. First, a comparison of all configurations of a scenario combined are given and the more general observations are discussed. Afterwards, the results will be compared separately based on the (A)TT fleet configuration and the more specific observations are discussed. Lastly, the results of the peak-load and off-peak-load scenarios are compared with each other.

For all comparisons in this section, the One-FEFS strategy is used as a sort of 'base' case to compare the other strategies to, as it is seen by some ATT developers as the default safe option for implementation.

7.1.1. Peak-Load Scenario

From the QC productivity chart in Figure 7.1, the first and foremost observation is that the ATT model performs significantly worse than the non-autonomous TT model, regardless of which ATT intersection strategy is chosen. From the different intersection strategies, it is visible that increasing the amount of ATTs in the fleet, does not necessarily increase the QC productivity as well. This phenomenon is mainly visible when comparing the 50 ATT and 60 ATT fleets. For the One-FEFS strategy the QC performance even decreases slightly going from 50 ATTs to 60 ATTs, signaling that congestion might have a larger influence with this strategy. From Figure 7.3, it is also visible that the amount of driven time spent in a queue increases steadily with the number of (A)TTs in the fleet, this is true for all intersection strategies and non-automated TTs as well.

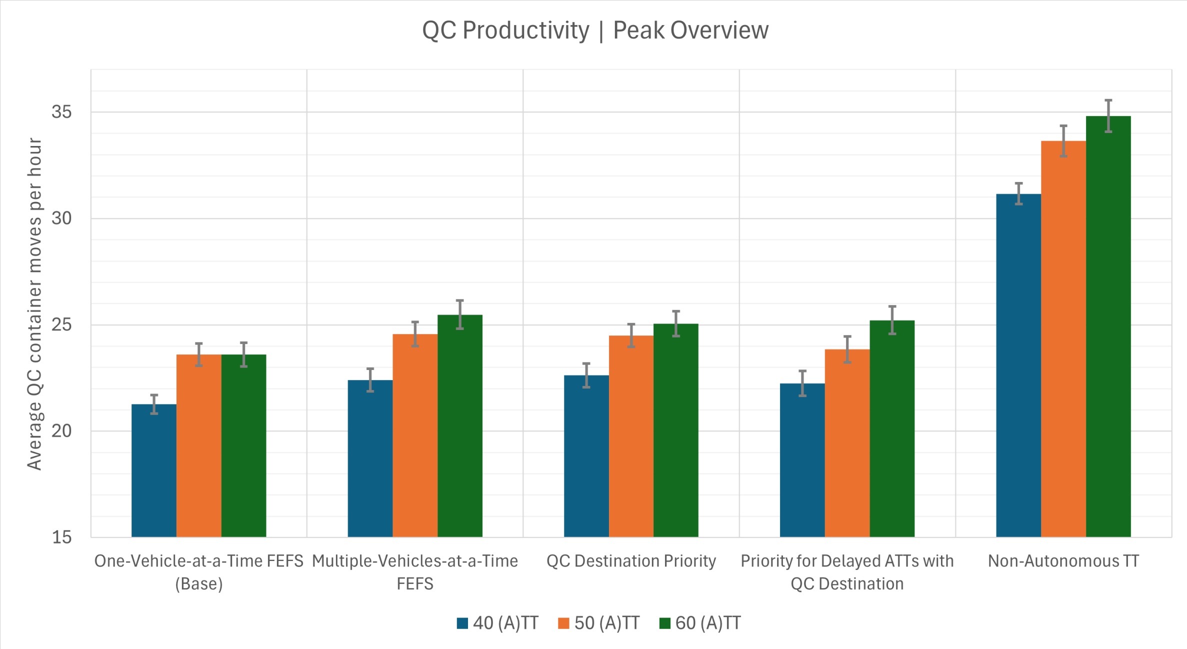

Figure 7.1: Overview of the QC productivity results for the various (A)TT fleet configuration tests in peak-load scenario

When comparing the intersection throughput from Figure 7.2 with the corresponding QC productivity from Figure 7.1, it can be seen that an increase in the one is nearly always related to an increase in the other. The intersection throughput also shows diminished increases in results when increasing the amount of ATTs in a fleet.

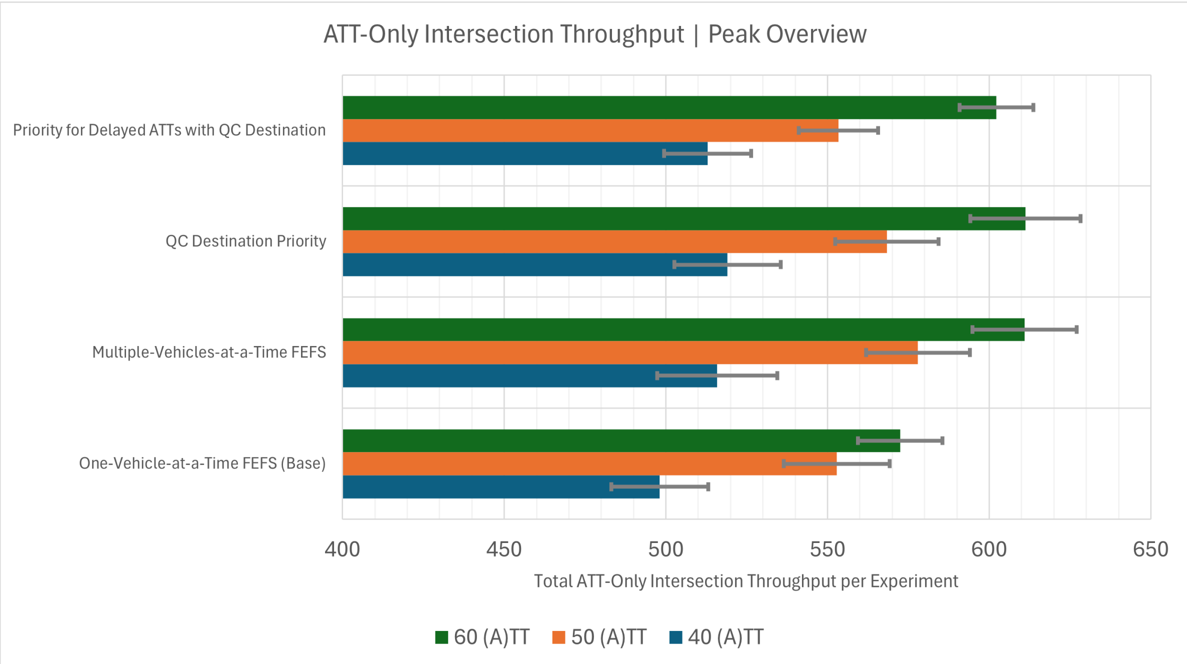

Figure 7.2: Overview of the intersection throughput results for the various (A)TT fleet configuration tests in peak-load scenario

From the drive status depicted in Figure 7.3, it can be seen that for all intersection strategies and ATT fleet sizes, a large share ranging between the 46% and 33% is spent on queuing for either an RTG or an intersection. This is significantly more that the share of time queuing by the non-autonomous TT model, which ranges from 33% to 17%. Between fleet sizes there is also a clear pattern, with the ATTs operating in a larger fleet having a significantly higher percentage of their drive status stent on standing still in a queue, than ATTs in smaller sized fleets.

With these large shares of queuing for the larger ATT fleet sizes and observations during the experiments that these queues often cause a propagation of congestion, it can be stated that the congestion of the terminal road network is a large cause of the inefficiency of the ATT model.

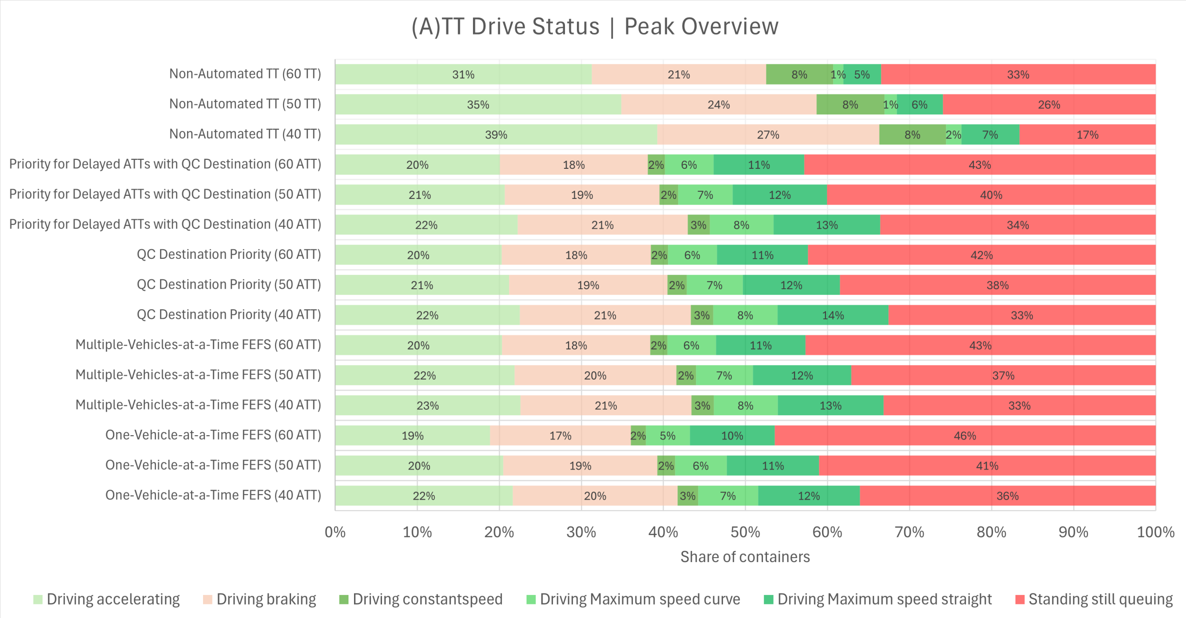

Figure 7.3: Overview of the drive status for the various (A)TT fleet configuration tests in peak-load scenario

40 (A)TT fleet configuration | Peak

The best performing intersection strategy for the 40 ATT fleet configuration, is the QC-Prio strategy. This is both in terms of QC productivity and intersection throughput, though it does not have a statistically significant difference with the two other multiple-vehicles-at-a-time on the intersection type strategies. There are statistically significant differences between the results of the One-FEFS and multiple-vehicles-at-a-time type strategies.

The QC productivity results of the 40 (A)TT fleet configuration tests are listed in Table 7.1 and visualised in Appendix Figure B.2. The intersection throughput results of the 40 (A)TT fleet configuration tests are listed in Table 7.2 and visualised in Appendix Figure B.4. The results of the T-test for this configuration are given in Appendix Figure B.3 for the QC productivity and B.5 for the intersection throughput.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
One-Vehicle-at-a-Time FEFS (Base)	21.27 per hour	0.0%	± 0.44	48	(2)
Multiple-Vehicles-at-a-Time FEFS	22.41 per hour	5.4%	± 0.53	42	(8)
QC Destination Priority	22.62 per hour	6.4%	± 0.56	46	(4)
Priority for Delayed ATTs with QC Destination	22.25 per hour	4.6%	± 0.58	57	(3)
Non-Autonomous TT	31.16 per hour	46.5%	± 0.49	28	(2)

Table 7.1: QC Productivity results for 40 (A)TT fleet configuration test in peak-load scenario

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
One-Vehicle-at-a-Time FEFS (Base)	498 vehicles	0.0%	± 13.02
Multiple-Vehicles-at-a-Time FEFS	516 vehicles	3.6%	± 16.16
QC Destination Priority	519 vehicles	4.2%	± 17.06
Priority for Delayed ATTs with QC Destination	513 vehicles	3.0%	± 11.38

Table 7.2: Intersection throughput results for 40 (A)TT fleet configuration test in peak-load scenario

50 (A)TT fleet configuration | Peak

In this configuration, the QC-Prio and Multi-FEFS strategy both perform nearly identical in terms of QC productivity, but the latter does have a higher intersection throughput. There is no statistically significant difference between the two, and thus both can be considered as best performing for this configuration. A more surprising result is that for this configuration, the Delay-Prio strategy performs nearly identically to the One-FEFS strategy, this for both the QC productivity and intersection throughput. They both perform statistically significant worse than the two other intersection strategies.

The QC productivity results of the 50 (A)TT fleet configuration tests are listed in Table 7.3 and visualised in Appendix Figure B.6. The intersection throughput results of the 50 (A)TT fleet configuration tests are listed in Table 7.4 and visualised in Appendix Figure B.8. The results of the T-test for this configuration are given in Appendix Figure B.7 for the QC productivity and B.9 for the intersection throughput.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
One-Vehicle-at-a-Time FEFS (Base)	23.76 per hour	0.0%	± 0.52	38	(22)
Multiple-Vehicles-at-a-Time FEFS	24.56 per hour	3.4%	± 0.57	53	(22)
QC Destination Priority	24.50 per hour	3.1%	± 0.53	62	(13)
Priority for Delayed ATTs with QC Destination	23.84 per hour	0.3%	± 0.61	49	(11)
Non-Autonomous TT	33.65 per hour	41.6%	± 0.71	28	(2)

Table 7.3: QC Productivity results for 50 (A)TT fleet configuration test in peak-load scenario

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
One-Vehicle-at-a-Time FEFS (Base)	553 vehicles	0.0%	± 16.34
Multiple-Vehicles-at-a-Time FEFS	578 vehicles	4.5%	± 16.07
QC Destination Priority	568 vehicles	2.8%	± 15.94
Priority for Delayed ATTs with QC Destination	553 vehicles	0.0%	± 12.25

Table 7.4: Intersection throughput results for 50 (A)TT fleet configuration test in peak-load scenario

60 (A)TT fleet configuration | Peak

For this configuration, the Multi-FEFS strategy performs the best both in terms of QC productivity, though it does not perform statistically significantly better than the other two multiple-vehicles-at-a-time on the intersection type strategies. All three of these strategies have statistically significantly higher QC productivity and intersection throughput than the One-FEFS strategy, in this configuration. The deviation in results became noticeably higher for this fleet configuration, with the confidence interval not decreasing noticeably and in certain cases even increasing when adding replications. This configuration also featured by far the most deadlocks, resulting in failed replications.

The QC productivity results of the 60 (A)TT fleet configuration tests are listed in Table 7.5 and visualised in Appendix Figure B.10. The intersection throughput results of the 60 (A)TT fleet configuration tests are listed in Table 7.6 and visualised in Appendix Figure B.12. The results of the T-test for this configuration are given in Appendix Figure B.11 for the QC productivity and B.13 for the intersection throughput.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
One-Vehicle-at-a-Time FEFS (Base)	23.60 per hour	0.0%	± 0.56	48	(28)
Multiple-Vehicles-at-a-Time FEFS	25.48 per hour	7.9%	± 0.66	51	(39)
QC Destination Priority	25.06 per hour	6.2%	± 0.59	52	(33)
Priority for Delayed ATTs with QC Destination	25.22 per hour	6.8%	± 0.65	44	(28)
Non-Autonomous TT	34.82 per hour	47.6%	± 0.74	37	(7)

Table 7.5: QC Productivity results for 60 (A)TT fleet configuration test in peak-load scenario

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
One-Vehicle-at-a-Time FEFS (Base)	572 vehicles	0.0%	± 15.00
Multiple-Vehicles-at-a-Time FEFS	611 vehicles	6.7%	± 18.56
QC Destination Priority	611 vehicles	6.7%	± 16.40
Priority for Delayed ATTs with QC Destination	602 vehicles	5.2%	± 13.49

Table 7.6: Intersection throughput results for 60 (A)TT fleet configuration test in peak-load scenario

7.1.2. Off-Peak-Load Scenario

As the off-peak-load scenario has a smaller ATT fleet driving on the same terminal road network as the peak-load scenario, it was expected that congestion would play a smaller role in the productivity of the terminal. This is largely visible in Figure 7.4, where an increase in fleet size corresponds with an increase in productivity. Do note that this increase is noticeably lower when going from 25 to 30 ATTs than when going from 20 to 25 ATTs, for all strategies except the Multi-FEFS. It is also very noticeable with the non-autonomous TT results. This does indicate that congestion still plays a role, even at these lower fleet sizes. The drive status of the (A)TTs in Figure 7.6 support this, as the share of the drive status, standing still queuing increases with the fleet size.

There is still a substantial difference in QC productivity between all strategies with the ATT model and the non-autonomous TT model. There is also no noticeable best performing intersection strategy for the ATT model in this scenario, as for each fleet size a different strategy performs best, also are the differences in QC productivity between strategies relatively small. The QC-Prio strategy did however perform the most consistently well across all fleet sizes.

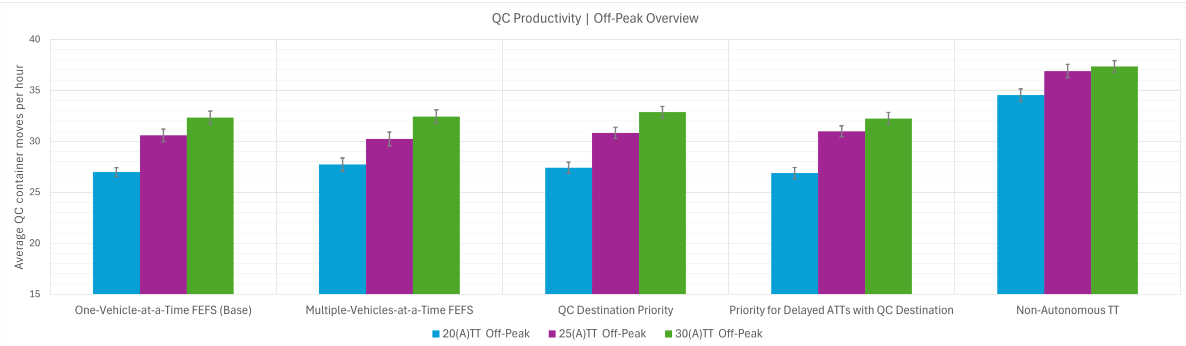

Figure 7.4: Overview of the QC productivity results for the various (A)TT fleet configuration tests in off-peak-load scenario

The same relation between QC productivity increase and fleet size increase, is also visible in the intersection throughput of Figure 7.5. Where the the same diminished returns are visible when going from a 25 to 30 ATT fleet when compared to going from a 20 to 25 ATT fleet.

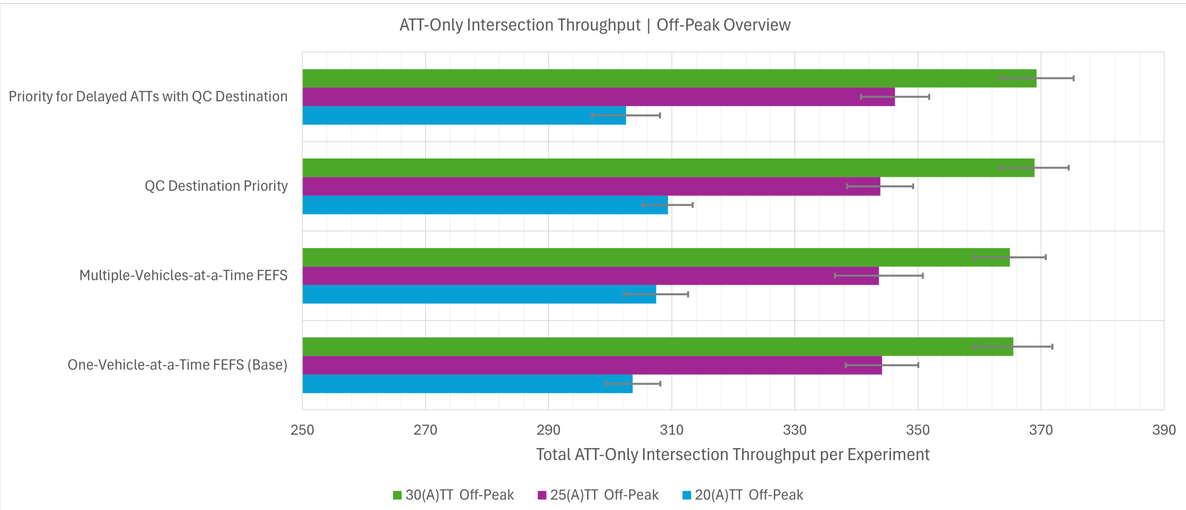

Figure 7.5: Overview of the intersection throughput results for the various (A)TT fleet configuration tests in off-peak-load scenario

Even in the off-peak scenario, the standing still queuing part of the drive status of Figure 7.6, is still a substantial part of the drive status of the ATTs, ranging from 20% to 31%. What does stand out, is that the standing still queuing percentages of all ATT strategies are very close together when comparing the respective fleet sizes, and the results of the ATT model and the TT model are not that far from each other either.

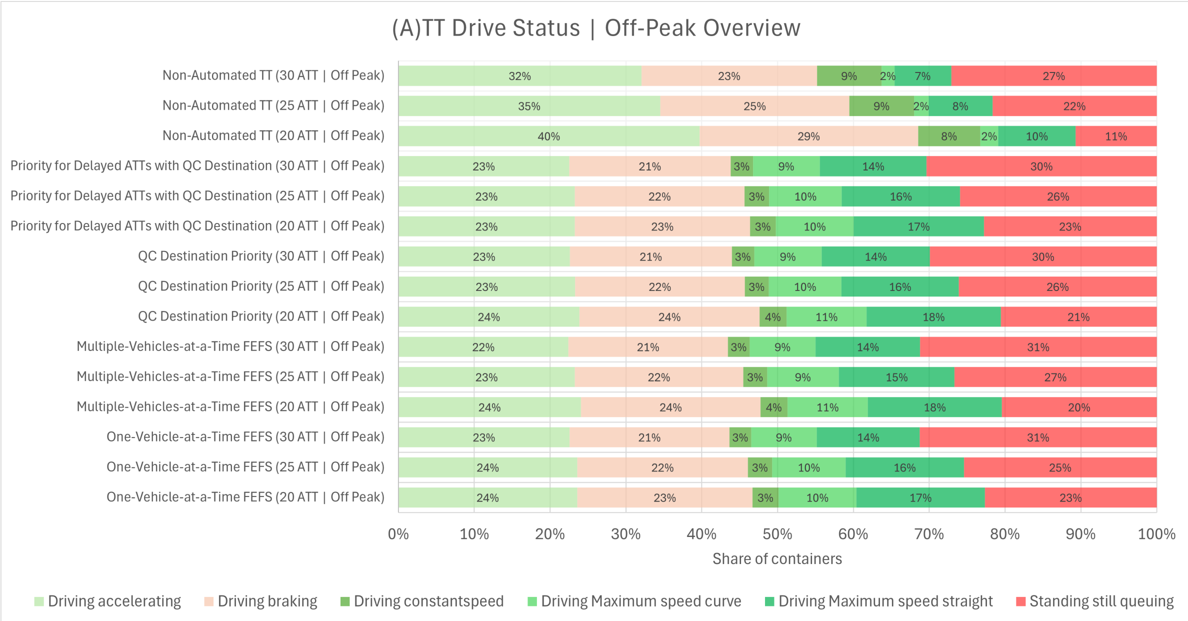

Figure 7.6: Overview of the drive status for the various (A)TT fleet configuration tests in off-peak-load scenario

20 (A)TT fleet configuration | Off-Peak

For this smallest fleet configuration, there are still some noticeable differences between intersection strategies, with the Multi-FEFS and QC-Prio strategies performing statistically significantly better than the One-FEFS and Delay-Prio strategies. The Multi-FEFS scored best on QC productivity, but had a slightly lower intersection throughput than the QC-Prio strategy.

The QC productivity results of the 20 (A)TT fleet configuration tests are listed in Table 7.7 and visualised in Appendix Figure B.14. The intersection throughput results of the 20 (A)TT fleet configuration tests are listed in Table 7.8 and visualised in Appendix Figure B.16. The results of the T-test for this configuration are given in Appendix Figure B.15 for the QC productivity and B.17 for the intersection throughput.

Configuration	**Average QC container moves**	**Change Percentage to Base**	**95 % Confidence Interval**	**Number of Replications**	
				Successful	(Failed)
One-Vehicle-at-a-Time FEFS (Base)	26.96 per hour	0.0%	± 0.44	60	(0)
Multiple-Vehicles-at-a-Time FEFS	27.72 per hour	2.8%	± 0.65	59	(1)
QC Destination Priority	27.42 per hour	1.7%	± 0.53	58	(2)
Priority for Delayed ATTs with QC Destination	26.87 per hour	-0.3%	± 0.55	56	(4)
Non-Autonomous TT	34.52 per hour	28.0%	± 0.62	29	(1)

Table 7.7: QC Productivity results for 20 (A)TT fleet configuration test in off-peak-load scenario

Configuration	**Average Intersection Throughput**	**Change Percentage to Base**	**95% Confidence Interval**
One-Vehicle-at-a-Time FEFS (Base)	304 vehicles	0.0%	± 4.49
Multiple-Vehicles-at-a-Time FEFS	307 vehicles	1.3%	± 5.18
QC Destination Priority	309 vehicles	1.9%	± 4.03
Priority for Delayed ATTs with QC Destination	303 vehicles	-0.3%	± 5.52

Table 7.8: Intersection throughput results for 20 (A)TT fleet configuration test in off-peak-load scenario

25 (A)TT fleet configuration | Off-Peak

This fleet configuration had some interesting results, as the results of all tested ATT intersection strategies were relatively close to each other, both for the QC productivity and the intersection throughput. Here the Multi-FEFS even performed slightly worse than the One-FEFS, but not with a statistical significant margin. The QC-Prio and Delay-Prio strategy did perform better than the Multi-FEFS strategy with a statistical significant margin, with the Delay-prio strategy having the highest QC productivity

The QC productivity results of the 25 (A)TT fleet configuration tests are listed in Table 7.9 and visualised in Appendix Figure B.18. The intersection throughput results of the 25 (A)TT fleet configuration tests are listed in Table 7.10 and visualised in Appendix Figure B.20. The results of the T-test for this configuration are given in Appendix Figure B.19 for the QC productivity and B.21 for the intersection throughput.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
One-Vehicle-at-a-Time FEFS (Base)	30.58 per hour	0.0%	±0.62	59	(1)
Multiple-Vehicles-at-a-Time FEFS	30.22 per hour	-1.2%	±0.67	59	(1)
QC Destination Priority	30.82 per hour	0.8%	±0.56	59	(1)
Priority for Delayed ATTs with QC Destination	30.97 per hour	1.3%	±0.53	60	(0)
Non-Autonomous TT	36.88 per hour	20.6%	±0.66	28	(2)

Table 7.9: QC Productivity results for 25 (A)TT fleet configuration test in off-peak-load scenario

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
One-Vehicle-at-a-Time FEFS (Base)	344 vehicles	0.0%	±5.88
Multiple-Vehicles-at-a-Time FEFS	344 vehicles	0.0%	±7.16
QC Destination Priority	344 vehicles	0.0%	±5.35
Priority for Delayed ATTs with QC Destination	346 vehicles	0.6%	±5.53

Table 7.10: Intersection throughput results for 25 (A)TT fleet configuration test in off-peak-load scenario

30 (A)TT fleet configuration | Off-Peak

Here the trend continues of nearly no differences in performance between the intersection strategies, as there is only a statistical significant difference between the QC-Prio and Delay-Prio strategies, with QC-Prio performing the best in terms of QC productivity. It is also noticeable that for this fleet size and scenario combo in particular, the QC productivity of the ATT model comes a lot closer to the non-autonomous TT model than it has done for all other test configurations.

The QC productivity results of the 30 (A)TT fleet configuration tests are listed in Table 7.7 and visualised in Appendix Figure B.14. The intersection throughput results of the 30 (A)TT fleet configuration tests are listed in Table 7.8 and visualised in Appendix Figure B.16. The results of the T-test for this configuration are given in Appendix Figure B.23 for the QC productivity and B.25 for the intersection throughput.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
One-Vehicle-at-a-Time FEFS (Base)	32.33 per hour	0.0%	±0.63	59	(1)
Multiple-Vehicles-at-a-Time FEFS	32.42 per hour	0.3%	±0.67	59	(1)
QC Destination Priority	32.85 per hour	1.6%	±0.57	60	(0)
Priority for Delayed ATTs with QC Destination	32.24 per hour	-0.3%	±0.58	60	(0)
Non-Autonomous TT	37.34 per hour	15.5%	±0.56	28	(2)

Table 7.11: QC Productivity results for 30 (A)TT fleet configuration test in off-peak-load scenario

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
One-Vehicle-at-a-Time FEFS (Base)	365 vehicles	0.0%	±6.38
Multiple-Vehicles-at-a-Time FEFS	365 vehicles	0.0%	±5.81
QC Destination Priority	369 vehicles	0.9%	±5.54
Priority for Delayed ATTs with QC Destination	369 vehicles	0.9%	±5.52

Table 7.12: Intersection throughput results for 30 (A)TT fleet configuration test in off-peak-load scenario

7.1.3. Comparing Peak and Off-Peak

For the appropriate comparison between the peak-load and off-peak-load scenarios, only the results of the pairs of corresponding fleet sizes should be compared to each other. These are the 20 and 40 (A)TT fleets, 25 and 50 (A)TT fleets, 30 and 60 (A)TT fleets.

Across the corresponding fleets of the ATT model, it is noticeable that the QC productivity gets a major increase in the off-peak scenario when compared to the peak scenario, with the largest increase occurring between the 30 and 60 ATT configuration, this has been visualised in Figure 7.7. It is important to note that there are the same amount of ATTs per QC across the corresponding fleets. As such, the difference in QC performance could be mainly attributed towards the difference in congestion on the terminal road network. This is in line with the findings of Gerrits, Mes, and Schuur, 2020, which also found that larger fleets of ATTs were more susceptible to congestion. It could also be argued then that the peak-load QC performances could approach their corresponding off-peak-load counterparts, when the congestion on the terminal road network would be eliminated.

It is also noticeable that these increases are significantly smaller when comparing the peak and off-peak scenarios of the non-autonomous TT. This fits the prior observations that the non-autonomous TT model suffers less from congestion.

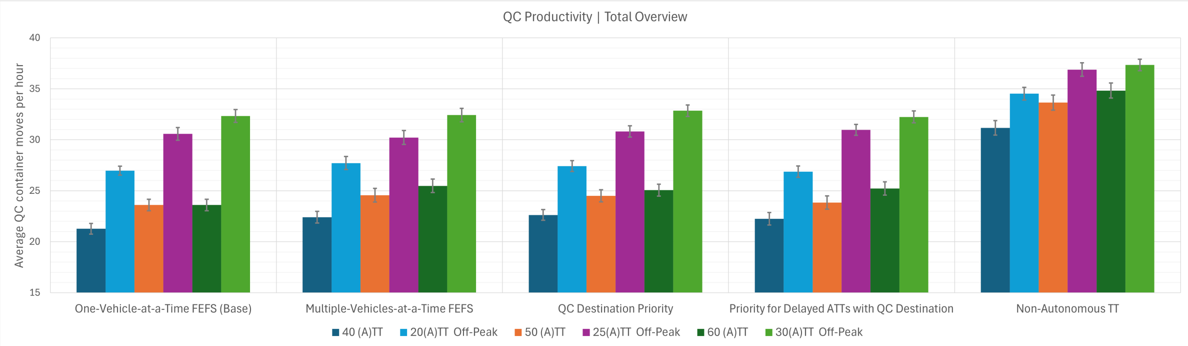

Figure 7.7: Total overview of all QC productivity results for both the peak- and off-peak-load scenarios

As expected are the intersection throughput results of the off-peak scenario a lot lower than the peak scenario ones, as these are related to the absolute fleet sizes. The 30 ATT configuration does have an interestingly low intersection throughput when compared to the 40 ATT configuration, as is visualised in Figure 7.8. A possible explanation for this could be that there are relatively less routes which cross ATT-only intersections in the off-peak scenario. This would also partially explain why the intersection strategies themselves have such a little effect on the intersection throughput.

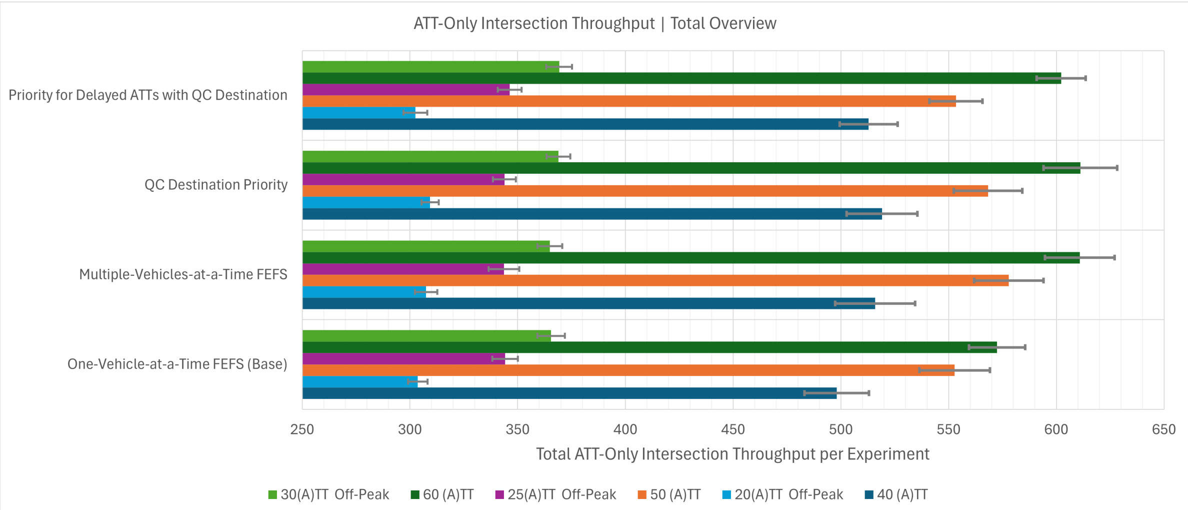

Figure 7.8: Total overview of all intersection throughput results for the peak- and off-peak-load scenarios

For both peak and off-peak scenarios, the move types of the QCs were logged and visualised if Appendix Figure B.26 and B.27.

7.2. Parameter Influence Tests

In this section the results of the parameter tests of the maximum speed of ATTs and perception time-step, are presented. The maximum speed tests were performed on the One-FEFS strategy, with a 40 ATT fleet configuration. While the perception time-step tests were performed on all intersection strategies with a 40 ATT fleet configuration and on the Multi-FEFS strategy, with a 50 ATT fleet configuration.

7.2.1. Maximum Speed for ATTs

It was expected that a higher maximum speed would coincide with a higher QC productivity and higher intersection throughput. This matches the test results, where a 5 km/h speed limit increase results in a 3.2% increase in QC productivity and a 1.0% increase in intersection throughput, while a decrease of 5 km/h results in a 0.6% decrease in QC productivity and 1.2 % decrease in intersection throughput, when compared to the base case of a 25 km/h speed limit. The QC productivity results of the maximum speed tests are listed in Table 7.13 and visualised in Figure 7.9. The intersection throughput results of the maximum speed tests are listed in Table 7.14 and visualised in Figure 7.10.

In term of statistic significance, there is a significant difference between the QC productivity of the 30 km/h max speed configuration and the other two max speed configurations. And there is a significant difference between the intersection throughput of the 20 km/h and 30km/h max speed configurations. All other test results of the maximum speed tests do not have a significant difference between them.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
Max. speed 20 km/h	21.15 per hour	-0.6%	± 0.60	30	(0)
Max. speed 25 km/h (base)	21.27 per hour	0.0%	± 0.44	48	(2)
Max. speed 30 km/h	21.95 per hour	3.2%	± 0.59	24	(6)

Table 7.13: QC Productivity results for max speed test

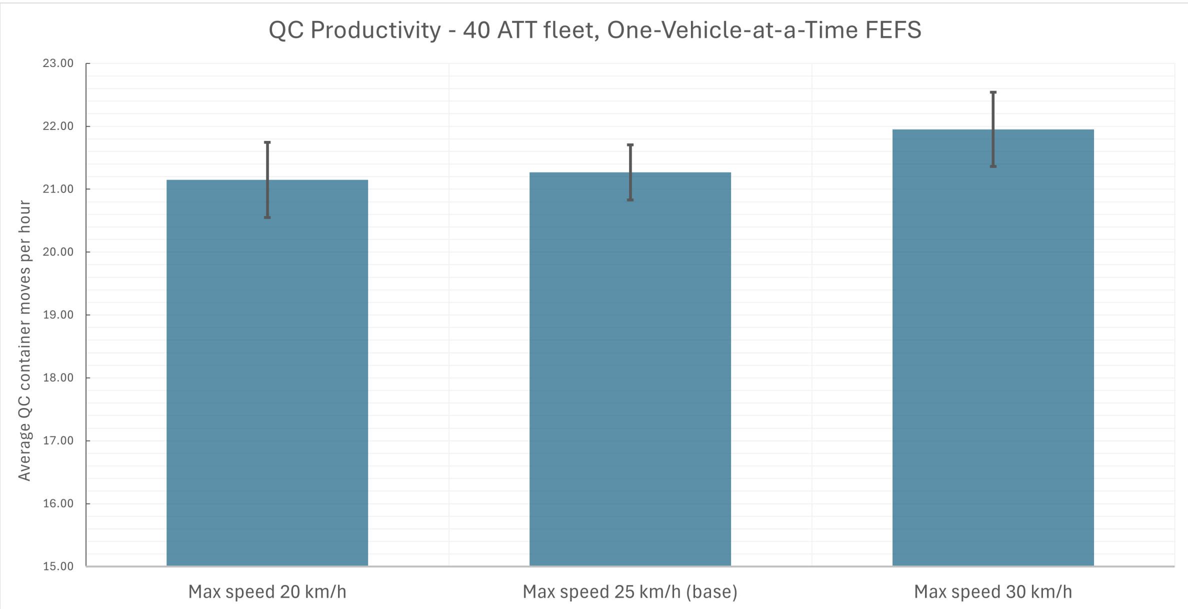

Figure 7.9: QC productivity results for max speed test

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
Max speed 20 km/h	492 vehicles	-1.2%	± 10.34
Max speed 25 km/h (base)	498 vehicles	0.0%	± 13.02
Max speed 30 km/h	503 vehicles	1.0%	± 8.54

Table 7.14: Intersection throughput results for max speed test

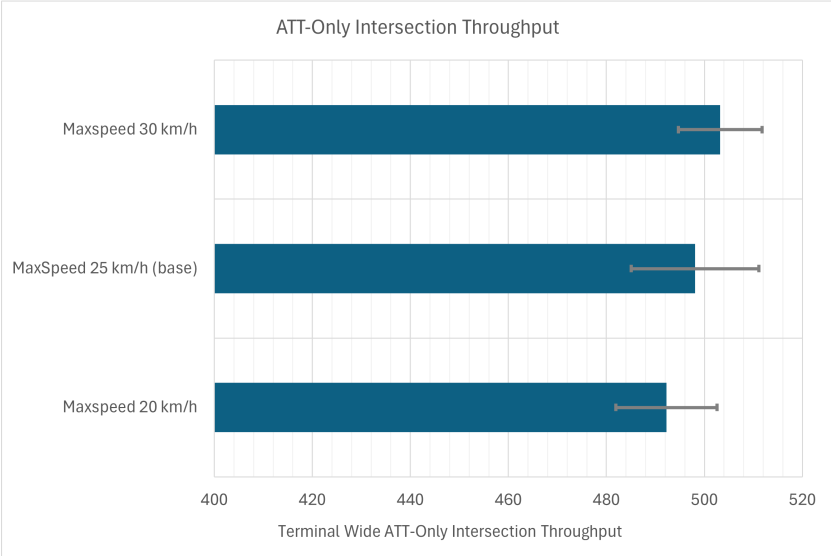

Figure 7.10: Intersection throughput results for max speed test

7.2.2. Perception Time-Step

The results of these tests should only be looked at in the context of their configurational pair, these pairs have the same color in the graphs and for each pair the Time-step 1s configuration has been designated as the base configuration of that pair.

It was expected that there would be a slight performance increase going from the 1 second time-step to the 0.1 second time-step. The result however does not show a consistent increase across the board for each pair. Between the pairs of test configurations, there is a range of an increase of 5.3% QC productivity to a decrease of -0.6% QC productivity, when going form the 1s time-step to the 0.1s time-step. With the increases in QC productivity being statistically significant, while the decreases are not. None of the intersection throughput results have any statistically significant differences between them. Though being a bit inconsistent, it can be said that in general the performance of the model does increase with a slower time-step.

The QC productivity results of the perception time-step tests are listed in Table 7.15 and visualised in Figure 7.11. The intersection throughput results of the perception time-step tests are listed in Table 7.16 and visualised in Figure 7.12.

As all other experiments were ran with a 1 second time-step, this implicates that these results could also deviate from what they would have been if the experiments were run with the 0.1 second time-step.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
40 ATT One-FEFS Time-step 1s (base)	21.27 per hour	0.0%	± 0.44	48	(2)
40 ATT One-FEFS Time-step 0.1	22.40 per hour	5.3%	± 0.68	33	(2)
40 ATT Multi-FEFS Time-step 1s (base)	22.41 per hour	0.0%	± 0.53	42	(8)
40 ATT Multi-FEFS Time-step 0.1s	22.32 per hour	-0.4%	± 0.92	23	(4)
40 ATT QC-Prio Time-step 1s (base)	22.62 per hour	0.0%	± 0.56	46	(4)
40 ATT QC-Prio Time-step 0.1s	22.48 per hour	-0.6%	± 0.68	24	(3)
40 ATT Delay-Prio Time-step 1s (base)	22.25 per hour	0.0%	± 0.58	57	(3)
40 ATT Delay-Prio Time-step 0.1s	23.26 per hour	4.5%	± 0.82	25	(2)
50 ATT Multi-FEFS Time-step 1s (base)	23.76 per hour	0.0%	± 0.52	53	(22)
50 ATT Multi-FEFS Time-step 0.1s	24.75 per hour	4.1%	± 0.71	43	(15)

Table 7.15: QC Productivity results for time-step test

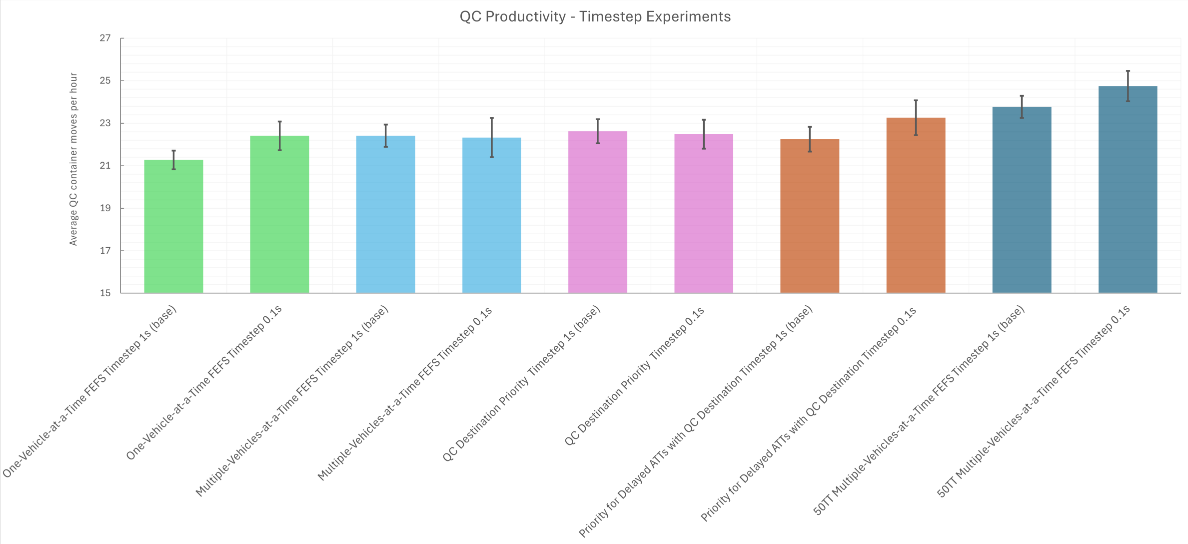

Figure 7.11: QC productivity results for time-step test

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
40 ATT One-FEFS Timestep 1s (base)	498 vehicles	0.0%	±13.02
40 ATT One-FEFS Timestep 0.1	509 vehicles	2.1%	±15.39
40 ATT Multi-FEFS Timestep 1s (base)	516 vehicles	0.0%	±16.16
40 ATT Multi-FEFS Timestep 0.1s	506 vehicles	-2.0%	±24.28
40 ATT QC-Prio Timestep 1s (base)	519 vehicles	0.0%	±17.06
40 ATT QC-Prio Timestep 0.1s	515 vehicles	-0.7%	±13.97
40 ATT Delay-Prio Timestep 1s (base)	513 vehicles	0.0%	±11.38
40 ATT Delay-Prio Timestep 0.1s	521 vehicles	1.5%	±15.71
50 ATT Multi-FEFS Timestep 1s (base)	578 vehicles	0.0%	±16.07
50 ATT Multi-FEFS Timestep 0.1s	580 vehicles	0.3%	±15.73

Table 7.16: Intersection throughput results for time-step test

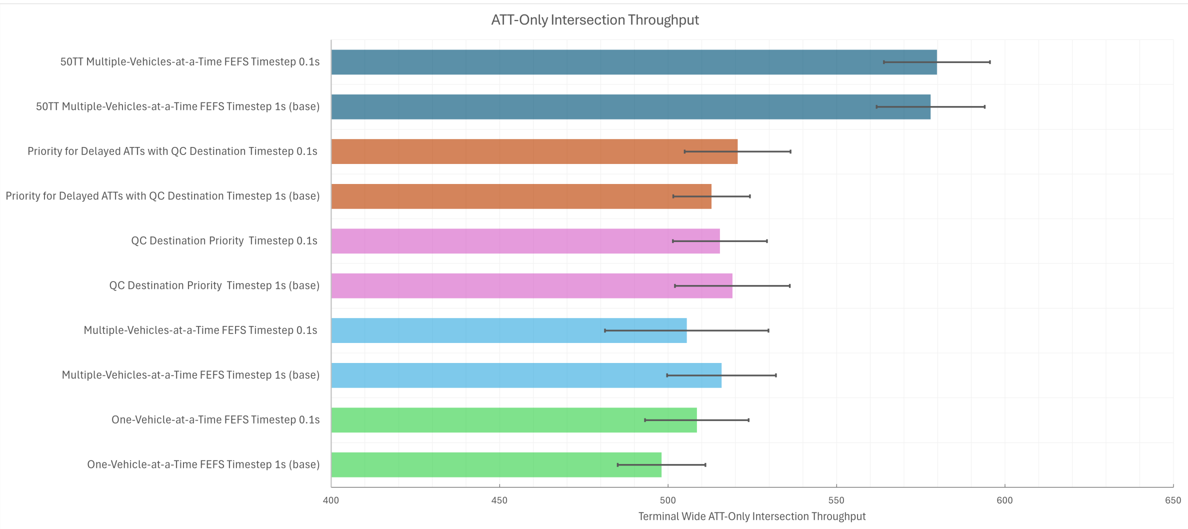

Figure 7.12: Intersection throughput results for time-step test

7.3. Tests with the Best Performing Intersection Strategy

The Multi-FEFS strategy has resulted in the highest QC productivity for both the 50 ATT as 60 ATT fleet configuration during peak-loads, although never really with a statistically significant margin. As such, the tests with larger road truck arrival rates and the conflict matrix without trailer sway will be done using this strategy. All tests in this section are performed under the peak-load scenario and a fleet size of 50 ATTs.

7.3.1. Road Truck Arrival Rate

There is a significant drop in QC productivity and intersection throughput when going from an arrival rate of 20 road trucks per hour to 50 road trucks per hour. As road trucks themselves do not drive near the QCs or on the ATT-only intersections, it can be deduced that the higher amount of road trucks on the terminal creates congestion on the highways and/or yard roads, which leads to a lower terminal performance.

It is worth noting, that the conducted experiments with the arrival rate of 100 trucks per hour scenario failed in quite a surprising way, as the ATT logic built into the road trucks was not able to handle the frequency with which the vehicles spawned at the gate. This caused large clusters of road trucks which were bunched up and overlapping at the gate, which can be seen in Figure 7.13. The result of this was that all of the replications of this experiment stopped to properly function at a certain point. As such, the results of the experiments with the arrival rate of 100 trucks per hour are not taken into account.

Figure 7.13: Bunching up of road trucks at the gate

The QC productivity results of the road truck arrival rate tests are listed in Table 7.17 and visualised in Figure 7.14. The intersection throughput results of the road truck arrival rate tests are listed in Table 7.18 and visualised in Figure 7.15.

Configuration	**Average QC container moves**	**Change Percentage to Base**	**95 % Confidence Interval**	**Number of Replications**	
				Successful	(Failed)
20 Road trucks per hour (Base)	24.56 per hour	0.0%	± 0.57	53	(22)
50 Road trucks per hour	23.05 per hour	-6.2%	± 0.71	46	(14)
100 road trucks per hour*	-	-	$\pm -$	0	(25)

Table 7.17: QC Productivity results for road truck arrival rate test

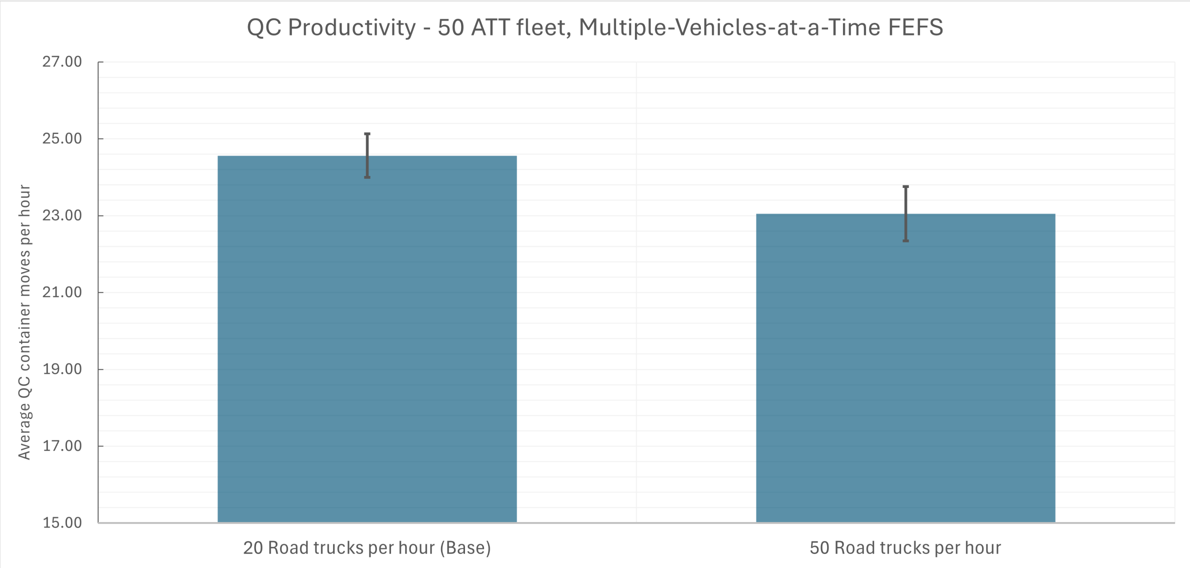

Figure 7.14: QC productivity results for road truck arrival rate test

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
20 Road trucks per hour (Base)	578 vehicles	0.0%	± 16.07
50 Road trucks per hour	543 vehicles	-6.1%	± 14.61
100 road trucks per hour*	-	-%	-

Table 7.18: Intersection throughput results for road truck arrival rate test

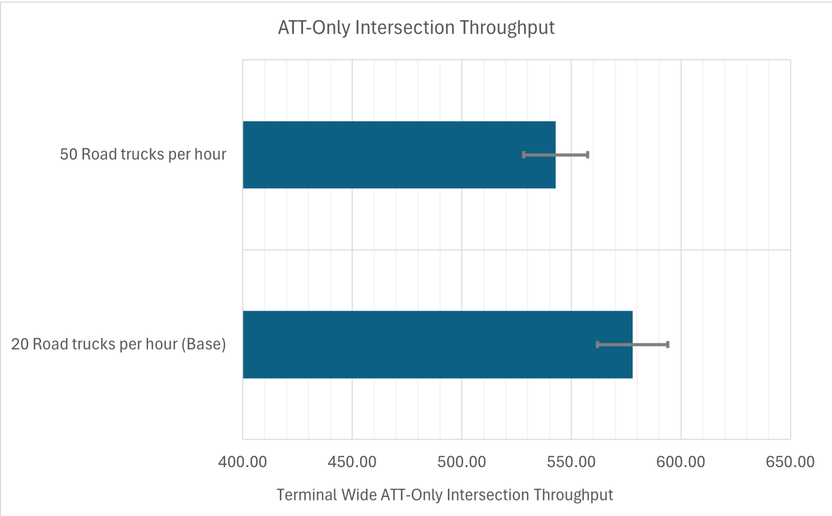

Figure 7.15: Intersection throughput results for road truck arrival rate test

7.3.2. Conflict Matrix With or Without Trailer Sway

It was expected that ignoring trailer sway at intersections would increase the QC productivity and intersection throughput. However, the results from this test present the opposite. There is an 2.2% decrease in QC productivity and an 1.6% decrease in intersection throughput when going from a FEFS strategy with trailer sway to a FEFS strategy without trailer sway. The QC productivity results of the trailer sway tests are listed in Table 7.19 and visualised in Figure 7.16. The intersection throughput results of the trailer sway tests are listed in Table 7.20 and visualised in Figure 7.17.

This outcome is strange, as a relaxation of constraints should logically lead to a better, or at least a comparable result. None of the outcomes of the trailer sway tests are statistically significant, so the difference might be (partially) attributable to a large variance in replications. Another possibility could be that the model still has some flaws in its implementation which might have flown under the radar of the verification and validation process.

Configuration	Average QC container moves	Change Percentage to Base	95 % Confidence Interval	Number of Replications	
				Successful	(Failed)
With Trailer Sway (base)	24.56 per hour	0.0%	± 0.57	53	(22)
Without Trailer Sway	24.03 per hour	-2.2%	± 0.64	33	(22)

Table 7.19: QC Productivity results for trailer sway test

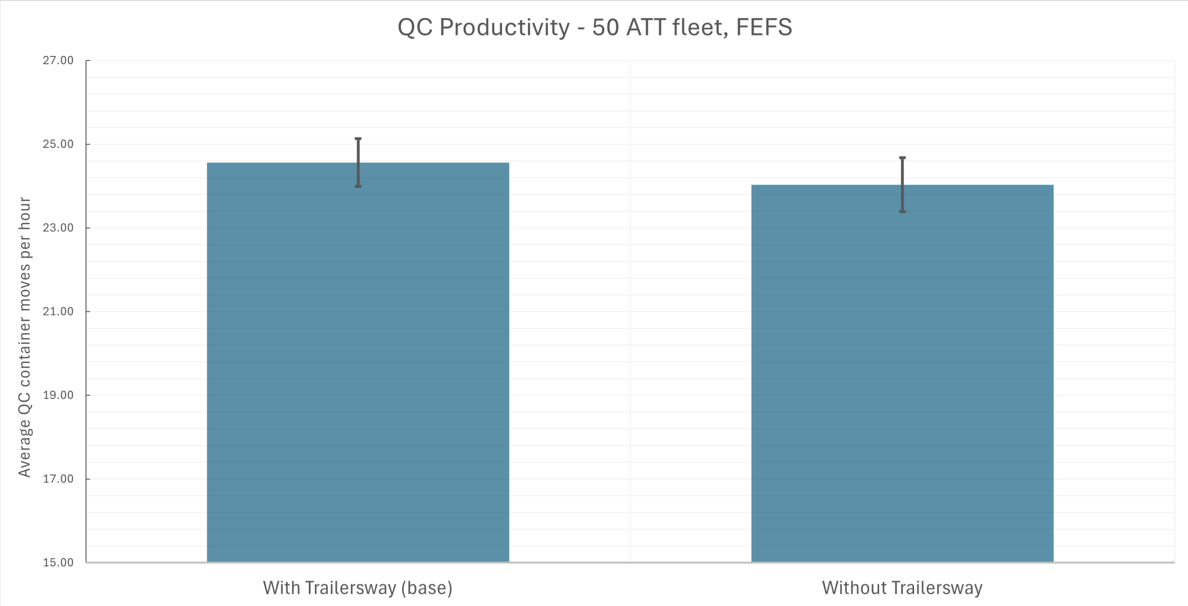

Figure 7.16: QC productivity results for trailer sway test

Configuration	Average Intersection Throughput	Change Percentage to Base	95% Confidence Interval
With Trailer Sway (base)	578 vehicles	0.0%	± 16.07
Without Trailer Sway	568 vehicles	-1.6%	± 12.19

Table 7.20: Intersection throughput results for trailer sway test

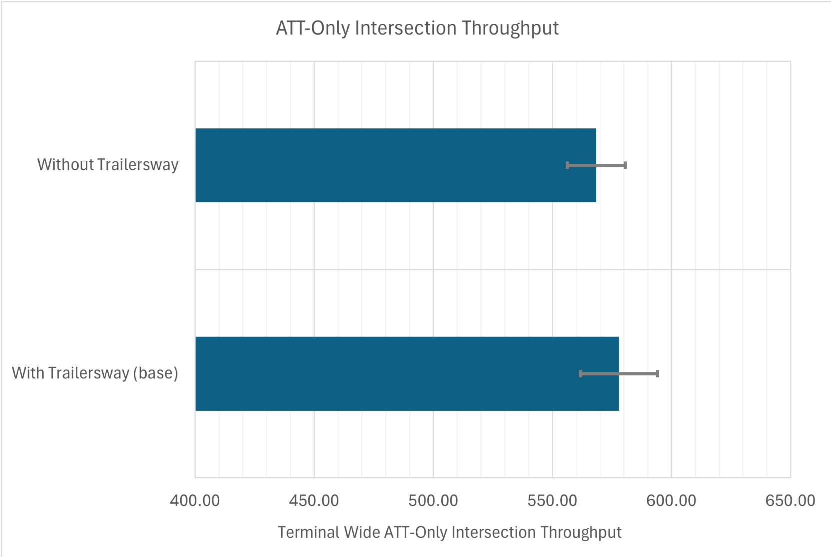

Figure 7.17: Intersection throughput results for trailer sway test

7.4. Reflection on the Results

There a few factors limiting the validity of the ATT model, which will have most certainly have had an impact on the results of the experiments. An overview of these limitations was given in Section 5.5. Mainly the absence of a more intelligent or dynamic routing system will have constrained the results of the experiments, especially in the configurations with larger ATT fleet sizes and road truck arrival rates. This is because the simple static routing induces traffic jams and even deadlock situations in certain parts of the terminal road network. This tendency for traffic jams in certain areas, has near certainly played a part in the large variance in results between replications using the same strategy and configuration. It was not uncommon to see a more than 10 container moves per hour difference in the QC productivity between two replications. Here the variance also increased with the amount of ATTs on the terminal.

This is partially explained by the proneness of the ATT model to congestion, especially when utilising large fleet sizes. Possibly if dynamic pathfinding and routing will be implemented in a future iteration of the ATT model, the performance of it could approach the performance of the TT model. It should however be noted that ATTs by design will probably not outperform human driven TTs in real world operations either. For now at least, are the QC performance values from the ATT model results not yet a valid indication for the real-life performance which these vehicles could achieve, and should thus not be used for anything else than the comparison within this study.

7.5. Conclusion of the Results

By concluding on the results, an answer is formulated to sub-question 5: *How do the different intersection strategies impact the operational performance of the ATT model, and how do the ATT performances compare to a model of a human controlled TT?*

From the comparative tests of intersection strategies under the peak-load scenario, it was found that switching from a one-vehicle-at-a-time intersection strategy type to a multiple-vehicles-at-a-time one, will generally increase the QC productivity and intersection throughput with a significant margin. This was not really a surprising outcome, but does signal that the style of ATT-only intersection coordination does impact the overall terminal performance in this scenario. It was also found that utilising either the Multi-FEFS or the QC-Prio intersection strategy has led to the best performances in terms of terminal productivity, with the former performing better at the higher ATT fleet sizes, and with no statistically significant differences found between the results of the two strategies. The Delay-Prio strategy did not perform best in any test, but only performed statistically significantly worse in the 50 ATT fleet configuration. In essence, has the difference between the tested intersection strategies little impact on the QC productivity under peak-load, as long as multiple vehicles are allowed on the intersection at once. Dependant on the fleet-size, an increase in QC productivity ranging from 1 to 1.9 containers per hour (increase of 5% to 8%), can be observed in the peak-load scenario when switching from a one-vehicle-at-a-time intersection strategy type to a multiple-vehicles-at-a-time one, which is a significant increase.

For the comparative tests with the off-peak-load scenario, it was found that the different ATT intersection strategies have little to no impact on the performance of the terminal when there is not a lot of traffic on the terminal road network, and there was not one intersection strategy which consistently outperformed the others. This is also not an surprising outcome, as there is less opportunity for congestion to happen near the intersections when there are less ATTs in a fleet. The QC-Prio strategy however did perform the most consistently well across the off-peak tests with an average increase of 0.5 containers per hour (2% increase) in terms of QC productivity when compared to the One-FEFS strategy.

When comparing the peak-load and off-peak-load scenarios, it was found that the test of the off-peak scenario had a significantly higher QC productivity than the tests of the corresponding peak-load scenario, with an approximate gap ranging from 5 to 8 containers per hour (24% to 31% increase), increasing with the fleet size. This difference in productivity could be attributed to higher levels of congestion during the peak scenario, and additionally it could be argued that the peak-load QC performances could approach their corresponding off-peak-load counterparts, when the congestion on the terminal road network would be eliminated. Through this comparison it could also be argued that congestion plays a large role in hampering the performance of the ATT model during a peak-load scenario.

From the parameter influence tests, it was found that an increase in the maximum speed limit for the ATTs corresponds with a small increase in QC productivity, which is an expected outcome. It was also found that the perception time-step has a varying impact on the performance of the ATT model and the QC productivity, with the slower time-step of 0.1 seconds performing both significantly better and slightly worse than the time-step of 1 second. Though being a bit inconsistent, it can be said that in general the performance of the model does increase with a slower time-step.

For the additional tests conducted on the Multi-FEFS strategy, it was found that a higher road truck arrival rate has a significant negative impact on the QC productivity and intersection throughput, while not directly interacting with either QCs or ATT-only intersections. In the test configuration with the conflict matrix without trailer sway, the most unexpected outcome of this thesis was found, as this configuration had a noticeably lower QC productivity and intersection throughput as the one with a conflict matrix which included trailer sway. This outcome is quite illogical, and despite the active search for a reason for this, no real explanation has been found.

The intersection throughput has been found to be positively related to the QC productivity in nearly all configurations, with an increase in the one mostly corresponding with an increase in the other. However, these increases are not always in proportion and in some cases a lower intersection throughput corresponds to a relatively higher QC productivity.
In the end, all tested ATT configurations performed significantly worse than the non-autonomous TT model it was based upon. However the gap in QC performance was noticeably smaller for the off-peak-load scenario than for the peak-load one, with an average approximate gap of 6 containers per hour for the off-peak-load scenario and 9 containers per hour for the peak-load scenario. Which means that going from the ATT model to the TT model will constitute an average increase of 28% in the off-peak-load scenario and an average increase of 42% in the peak-load scenario.

8 Conclusion

In this chapter the overall conclusion of the thesis is formulated, in order to answer the main research question: **How does the intersection strategy of autonomous terminal tractor-only intersections influence the productivity of an RTG-based terminal?** To fully answer the main research question, five sub-questions were formulated. First, the answers to these sub-questions are discussed, afterwards an answer to the main research question is formulated.

Sub-Question 1: **How does an RTG-based terminal system function, which operational processes are present on it and how can the operational performance of it be measured?**
The chosen RTG-based container terminal is a terminal where RTGs and ATTs are used as equipment for the transportation of containers within the terminal. The terminal typically features a parallel layout. The horizontal transport of containers is facilitated by ATTs for container moves within the terminal, and by road trucks for the horizontal transport of containers entering or leaving the terminal by road. RTGs are used to move containers between horizontal transport vehicles and the yard stacks, and QCs are used to move containers between the vessel and ATTs.
Within the scope of this analysis, four operational processes which occur on an RTG-based terminal were discussed. The process of moving a container from the vessel into a stack block, and vice-versa, using a QC, an (A)TT and a RTG. As well as, the process of moving a container from the gate into a stack block, and vice-versa, using a road truck and a RTG.
In terms of operational performance measurements of container terminals, the most relevant were found to be the container throughput or QC productivity of the terminal, measured in TEU or containers in a given time horizon.

Sub-Question 2: **How does the internal system and control structure of an ATT function, and how does the ATT interact with other vehicles?**
ATTs are designed to operate in a HDV-(C)AV mixed-traffic environment. To perceive other vehicles around them, they utilise a set of sensors. The base components of this sensor set almost always consist out of at least a LiDAR, Camera and Radar. The signals coming from these sensors are combined in a process called sensor fusion, to combine the strengths and mitigate the weaknesses of each sensor.
ATTs in a container terminal operate within a multi-agent multi-layer control structure. At the strategic control layer there is the terminal operating system (TOS). In the tactical control layer, there is the fleet management system, which also includes the intersection management system (IMS). At the operational control layer, the vision and actuation module of each ATT are situated. Here ATTs can not directly communicate with each other, so there is a decentralised control structure.
Everywhere within their operational area, ATTs could have interactions with other ATTs. Their operational area also overlaps largely with the operational area of the road trucks, and interactions can occur anywhere within this overlap. ATTs also have interactions with RTGs and QCs whenever there are containers loaded or unloaded from the trailer of the ATT.
On the RTG-based terminal, there are ATT-only intersections at intersections of highways and the apron, and there are mixed-traffic intersections at the intersections of yard-roads and highways.

Sub-Question 3: **What is currently known in the literature about simulating ATTs/AVs and ATT/(C)AV/AGV intersection strategies?**
There have not been many studies on the subject of ATTs, mainly because they are still a recent development. The few available studies have mainly focused either on overall ATT efficiency or traffic rules for mixed traffic intersections. For these mixed traffic intersections, it was found that dynamic traffic rules with priority for either ATTs

or road trucks, or ATT-only lanes, dependant on ATT to road truck ratio would lead to the theoretic most efficient intersection strategies in these cases.
In terms of the methods used for ATT simulation studies, these have mainly been conducted using discrete event simulation. AV simulation studies on the other hand, have mainly used microscopic traffic simulations.
There have been numerous studies on CAV-only intersections, here the FCFS strategy has been utilised in each featured study as a benchmark, to which either an amended FCFS strategy or non-FCFS strategy has been tested. All of the featured CAV-intersection studies only utilised a one-intersection layout as a test configuration.
AGV based systems in container terminals usually do not feature the same type of intersections as (A)TT based terminals. The way scheduling conflicts are resolved however, does bear a resemblance to the way intersection conflicts at ATT-only intersection could be handled, with the FCFS strategy mostly being used as a benchmark for novel strategies.

Sub-Question 4: **How can the controller of an ATT be modelled in a microscopic discrete event simulation to be a valid representation of ATTs in real-life?**
The model of the ATT is based on the existing TT model of Portwise, here some input values have been changed to reflect the performance of a real-life ATT development. The ATT model includes the model of the ATT controller, and together were designed following these requirements: have a vehicle detection system akin to the sensors on the real-life ATT, and a rule-based actuation system which translates inputs from sensors and directives from the IMS into acceleration and braking actions for the ATT.
The ATT controller model has been developed to represent how a real-life ATT controller could function. It includes a main decision making logic, which uses the perception of the ATT, the overlap of its path with other vehicles and their paths, and the location of the ATT in relation the infrastructure, to determine its decisions with regard to actuation. This is coordinated by three sets of rules within the ATT controller model: the path conflict-, buffer interaction- and yard interaction rules.
The model of the IMS has been developed to coordinate the access of the ATTs to the ATT-only intersections. It does this by utilising an entry-and exit check to determine if an ATT can cross the intersection without stopping. Dependant on the intersection strategy, it also utilises a matrix-check using the conflict matrix, to determine if multiple vehicles can safely enter the intersection together. There have been four intersection strategies included in the IMS: One-Vehicle-at-a-Time, First-Eligible-First-Serve (One-FEFS), Multiple-Vehicles-at-a-Time FEFS (Multi-FEFS), QC Destination Priority (QC-Prio) and Priority for Delayed ATTs with QC Destination (Delay-Prio).
All models made for this thesis have been verified using code walkthroughs and traces, and have been validated through observing the animations produced by the simulation software. There are still some discrepancies between the model of the ATT and ATT controller, and how they would function in real life. This is mainly that the ATT model is unable to overtake stationary vehicles which are congesting its current path, making the model overall more prone to congestion which in turn negatively impacts the productivity of the terminal. A large part of this could be solved in the future by including dynamic routing and pathfinding in the ATT model.

Sub-Question 5: **How do different intersection strategies impact the operational performance of the ATT model, and how do the ATT performances compare to a model of a human controlled TT?**
By conducting experiments with these developed models and intersection strategies, it was found that the influence of the intersection strategy in ATT-only intersections on the productivity of the terminal is significant in a peak-load scenario. In this scenario it was found that utilising either the Multi-FEFS or the QC-Prio intersection strategy has lead to the best performances in terms of QC productivity, with the former performing better at the higher ATT fleet sizes, and with no statistically significant differences found between the results of the two strategies. There was however a significant increase in QC performance ranging from 1 to 1.9 containers per hour (increase of 5% to 8%), when going from a strategy where only one-vehicle-at-a-time was allowed on the intersection to a strategy where multiple-vehicles-at-a-time were allowed on the intersection. An increase in the ATT fleet size has also been observed to lead to an increase in queuing time per ATT, which goes paired with a larger amount of congestion on the terminal network.
The experiments with the off-peak scenario showed that there is nearly no influence of the intersection strategies on the terminal productivity during these kinds of operations. As such, there is not really one strategy outperforming all others in this scenario, however the QC-Prio strategy did perform the most consistently well across the fleet sizes in this scenario, with an average increase of 0.5 containers per hour (2% increase) in terms of QC productivity when compared to the One-FEFS strategy. When comparing the results of the peak and off-peak scenarios, it was found that the off-peak scenario vastly outperformed the peak scenario in terms of QC performance, with an approximate gap ranging from 5 to 8 containers per hour (24% to 31% increase), increasing with the fleet size. This indicates that congestion of the terminal road network during peak operations is a significantly hampering the performance of the ATT model.
Every configuration of the ATT model had a significantly lower QC productivity than the benchmark non-autonomous TT model. Here the gap in QC performance of the off-peak-load scenario was smaller than of the peak-load one, with an average approximate gap of 6 containers per hour for the off-peak-load scenario and 9 containers per hour

for the peak-load scenario. Which means that going from the ATT model to the TT model will constitute an average increase of 28% in the off-peak-load scenario and an average increase of 42% in the peak-load scenario.

Main Research Question: **How does the intersection strategy of autonomous terminal tractor-only intersections influence the productivity of an RTG-based terminal?**
The degree of influence the strategy of an ATT-only intersection has on the productivity of an RTG-based terminal, has been found to be dependant on the ATT fleet size. Here the lower fleet sizes (20 to 30 ATTs), which were tested with the off-peak-load scenario, showed no significant differences in QC productivity between the different tested intersection strategies. While the higher fleet sizes (40 to 60 ATTs), which were tested with the peak-load scenario, did show a significant increase in QC performance ranging from 1 to 1.9 containers per hour (increase of 5% to 8%), when going from a strategy where only one-vehicle-at-a-time was allowed on the intersection to a strategy where multiple-vehicles-at-a-time were allowed on the intersection.
As congestion was also observed to increase with fleet size, it shows that at smaller fleet sizes there are not enough ATTs which want to cross the same intersection at the same time, that changing intersection strategies has any significant effect on their performance within the terminal. At higher fleet sizes, ATT-only intersections become larger bottlenecks, hence the more influence changing the intersection strategy has on the overall terminal performance in these configurations. For the One-FEFS strategy, the QC performance even decreases slightly going from a 50 ATT to 60 ATT fleet, which is due to the added congestion these 10 extra vehicles produce.
As the less congested off-peak-load smaller fleets had a QC productivity which was 5 to 8 containers per hour higher than the peak-load larger fleets (increase of 24% to 31%), while having the same amount of ATTs per QC, it can be concluded that congestion greatly hampers the terminal productivity, with the current ATT-model. The proposed intersection strategies only alleviate a part of this congestion, as its influence on the QC productivity is found to be less than 2 containers per hour.
In terms of best performing intersection strategies within this thesis, it has been found that the QC-Prio strategy performed the most consistently well across the fleet sizes in the off-peak-load scenario, with an average increase of 0.5 containers per hour (2% increase) in terms of QC productivity when compared to the One-FEFS strategy, though this is not a statistically significant difference. For the peak-load scenario, it has been found that the QC-prio scored best on the lower (40 ATT) fleet configuration test, with a QC productivity increase of 1.3 containers per hour (6% increase) over the One-FEFS strategy. The Multi-FEFS strategy was found be the best performing strategy at the higher (60 ATT) fleet configuration test, with a QC productivity increase of 1.9 containers per hour (8% increase).
Every configuration of the ATT model had a significantly lower QC productivity than the benchmark non-autonomous TT model, with it having an approximately 6 containers per hour lower performance for the off-peak-load scenario and 9 containers per hour lower performance for the peak-load scenario (increase of 28% and 42% respectively, going from ATT model to TT model).

9

Reflection and Recommendations

9.1. Reflection

Although the designed ATT model has been a large transformation of the TT model it was based on already, it is not yet complete. At this point, it seems more like the first half of the creation of a valid and robust ATT simulation model. As such, it is encouraged to take the findings from this thesis and the model of the ATT and further complete it. This can mainly be done by designing solutions for the current limitations of the model.

The largest limitation of the ATT model, is that the ATTs are bound to the route they are given at the time of accepting their job, and they can never deviate from that given route. This leads to unnecessary congestion on lanes, where there is room for potential overtakes in the lane next to it. This absence of a dynamic routing component also hampers the validity of the ATT model, as ATTs are expected to have this feature in real life operations. It is due to this reason that there are more traffic jams in the model than would be in real life, and as such are the QC performance values from the ATT model results not yet indicative for the potential real-life ATT performance.

9.2. Recommendations

The recommendations for further studies are split into two categories. One for future research utilising the model proposed in this thesis and another for future research into ATT simulation models in general. Even though they are split this way, these two sets of recommendations can possibly be helpful for any research into ATT simulation models.

9.2.1. Further Research with the Proposed ATT Model

For a further study with the model proposed in this thesis, the following steps are recommended:

1. **Include dynamic routing and pathfinding in the ATT model**
   As stated before in the validation process of the ATT model, the current model not yet a complete and valid representation of how an ATT would operate in real-life. The main factor for this, is the inability of the ATT model to change lanes while it is mid-route, which propagates an unnecessary amount of congestion and deadlocks. In its current form, the ATT model would wait behind a stationary vehicle, even when the lane next to it is free to overtake the vehicle. Including a system which can detect if there is a less congested route possible by facilitating a lane change, can solve these issues. The implementation of such a dynamic routing system has been explored as a possibility for this thesis, but was left out of scope due to time constraints. The largest pitfall for the design and implementation of such a system is robustness, i.e. that the system is able to facilitate these lane changes in multiple places within the terminal, without introducing new problem situations to the ATT model.
2. **Add a more realistic road truck model**
   Currently within the model, the road trucks utilise the same logic as the ATTs for their driving behaviour. This makes for problematic situations when there is a large road truck arrival rate (100 per hour or above), as the logic is not able to handle such high frequencies of spawning at the gate. Furthermore, by utilising the ATT logic this way, the model is not really able to simulate ATTs within mixed traffic operations. By developing a road truck model which is more realistic in the sense of human driver behaviour and which can prevent the bunching problem at high spawn rates, mixed traffic operations can be simulated in a more accurate and realistic way.

3. **Test with other intersection strategies**
Only four intersection strategies have been featured within this thesis study, which is not by any means exhaustive. There are many other possible intersection strategies thinkable which were not featured within this study. It is expected that there are still a lot of possible intersection strategies which will perform better than the ones featured in this study. A small list of possible additional strategies include:

    - Adaptive traffic-light-type phase structure (an implementation of this strategy had been attempted for this thesis, but it was found that the entry-and exit check of the IMS was currently to difficult to combine with an adaptive traffic-light-type phase structure in a robust way)
    - Maximise the number of vehicles at once on the intersection
    - Minimise length of queue at intersection
    - Minimise deceleration of vehicles at the intersection
    - Minimise average queuing time of vehicles at the intersection

4. **Optimise model for simulation speed**
With the way which the current ATT model is designed, its simulation speed slows exponentially with the amount of ATTs and road trucks on the terminal. This is because each added vehicle has to run through the vision loop and inspect the path of each vehicle within its visible range, which also increases with the number of vehicles. This makes the simulation speed for large ATT fleets and especially for scenarios with a high arrival rate of road trucks, very slow. To make the ATT model more usable for larger simulations, it is recommended to rework the way these vehicles check their surroundings, such that they are able to run more efficiently within a discrete event simulation.

9.2.2. Further Research on ATT Simulations

For a further study in the realm of ATT simulations in general, the following additional recommendations are given:

1. **Develop strategies to ease congestion**
Congestion in terminals operating with ATT-fleets, is still a unresearched topic. This while it has been observed to be a significant contributor to inefficiencies within the ATT-model. As ATTs could in theory be directed by the FMS to act in a way which minimises the congestion of the terminal as a whole, a sort of theoretical system optimal way of coordinating ATTs on a terminal could be researched. The influx of human driven road trucks onto the terminal, does make this system more complex to design. Though, one could design a system where the FMS knows the exact location of each road truck, through some sort of V2I type interaction. Simulating such a system should be significantly simpler than testing it in real-life, and through a simulation, it can be tested if such a system could minimise or even completely eradicate congestion on the terminal road network.
2. **Develop a model using real-life operations**
At the beginning of this thesis project (November 2023) there were only a handful of ATT concepts which have been tested in terminal operations, and mostly only in very small fleet configurations. As such, it is more difficult to model these ATT concepts, as there are only a limited amount of resources on their real-life behaviour in fleet. Within the coming years, ATTs will most likely be implemented in a much larger scale within some RTG-based terminals. This will be a perfect opportunity to develop a more realistic ATT simulation model, as the behaviour of these vehicles can be observed in more detail and in more situations.
3. **Perform tests with varied road layouts** There have been no studies yet on how variations in the terminal road layout impact the efficiency of the terminal. In this thesis there has also only been one road layout used to perform all experiments with. Therefore it is not known what the impact would be on ATT based operations when lanes would change direction or when buffers would change location. It is possible that a more efficient road layout could be found or designed especially for interactions with ATTs. One possible design direction could be to dynamically change the lane directions for ATT-only lanes, dependant on the amount of ATTs that have a destination at the yard or QC.

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A

Scientific Paper

The Influence of Intersection Strategies of Autonomous Terminal Tractor-Only Intersections on the Productivity of an RTG-based Container Terminal

A Simulation Case Study at Portwise

T.A. Nooyens

Autonomous terminal tractors (ATTs) are a current development as a driver-less alternative to terminal tractors (TTs). This paper focuses on the integration of these ATTs in a rubber-tired-gantry (RTG)-based container terminal, and more specifically looking at how strategies for ATT-only intersections could influence the productivity of the terminal. For this study, a discrete-event simulation model of an ATT, ATT-controller and intersection management system (IMS) were designed. Within the IMS, four intersection strategies were developed: One-Vehicle-at-a-Time First-Eligible-First-Serve (One-FEFS), Multiple-Vehicles-at-a-Time First-Eligible-First-Serve (Multi-FEFS), Quay-Crane Destination Priority (QC-Prio) and Priority for Delayed ATTs with QC Destination (Delay-Prio). These intersection strategies were tested in a peak-load and off-peak-load scenario, on a model of an RTG-based terminal, with configurations of varying fleet sizes. Here was found that the intersection strategies had a small influence on the QC productivity in the peak-load scenario, and a negligible influence in the off-peak-load scenario. Utilising either the Multi-FEFS or the QC-Prio strategy leaded to the highest terminal performance. In the simulation model, the ATT performed significantly worse than the existing non-autonomous TT, in every configuration.

1. Introduction

In the world of container terminals, autonomous terminal tractors (ATTs) are currently being developed as a driver-less alternative to human-driven terminal tractors (TTs) (EasyMile, 2023). Unlike traditional automated guided vehicles (AGVs) found in container terminals, ATTs are equipped with sensor packages which allows them to reliably detect other vehicles, and as such operate in mixed traffic with human driven vehicles (HDVs) (AI-Drivers, 2023). This way, ATTs can be implemented into existing rubber tired gantry (RTG)-based container terminals which have human driven road trucks on the terminal road network.

The RTG-based container terminal used as a base for this study, is a terminal where RTGs and ATTs are used as equipment for the transportation of containers within the terminal, and which typically features a parallel layout. ATTs have the most interactions with other ATTs, as they can interact with each-other at every point on the terminal road network. They also have interactions with road trucks on some terminal roads, but not on the quay road or apron (Adriatic-Gate-Container-Terminal, 2020). There are thus some intersections of highways and aprons, where only ATTs should come during normal operations, the locations of these intersections are visualised in Figure 1. As there are only autonomous vehicles interacting with these ATT-only intersections, specialised intersection management strategies can be used to regulate the flows of ATTs at these intersections.

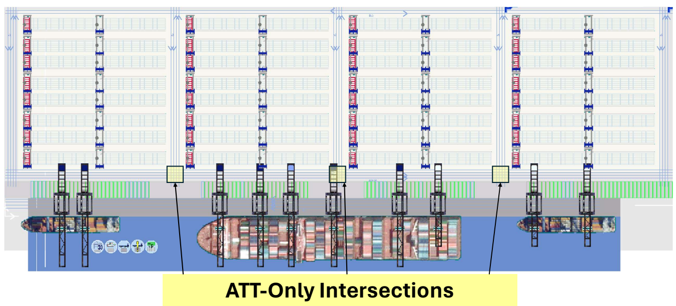


Figure 1. Locations of ATT-only intersections

There have not been many studies on the subject of ATTs, mainly because they are still a recent development (Gerrits and Schuur, 2022). The few available studies have focused either on overall ATT efficiency or traffic rules for mixed traffic intersections. There have been numerous studies on the intersection strategies of connected autonomous vehicle

(CAV)-only intersections, though all of the featured CAV-intersection studies only utilised a one-intersection layout as a test configuration. There is thus a research gap on how the intersection strategies of ATT-only intersections can influence the productivity of a container terminal. This leads to the main research question:

"How does the intersection strategy of autonomous terminal tractor-only intersections influence the productivity of an RTG-based terminal?"

The main method with which this question will be answered in this paper, is through the design of an ATT model, an ATT-controller model and an intersection management system (IMS) model, with which simulation experiments have been performed featuring different intersection strategies. These three models have been built into the TIMESQUARE terminal simulation environment of Portwise, which is made in the discrete-event simulation software eM-plant, to simulate the operations of ATTs within an RTG-based terminal. Preliminary to the design of these models, a system analysis of the RTG-based terminal and the ATT itself have been conducted, as well as a literature research on the simulation of ATTs/AVs and ATT/(C)AV/AGV intersection strategies.

2. Methodology

In this section, the research methods are discussed with which have been used in this study.

There were two system analyses conducted, one of an RTG-based terminal and one of an ATT, including the interactions the ATT has with other vehicles on the terminal.
A literature study has been conducted on the topics of simulating ATTs/AVs and ATT/(C)AV/AGV intersection strategies.
A model for discrete-event simulation has been designed for an ATT, the controller of an ATT and an intersection management system (IMS).
Experiments were conducted with the designed models using discrete-event simulation, with differing intersection strategies and with an existing model of a human controlled TT as a benchmark.

3. System Analysis | RTG-Based Terminal

An RTG-based container terminal is a terminal where RTGs and (A)TTs are used as equipment for the transportation of containers within the terminal. The terminal typically features a parallel layout, which means that the stack blocks in the yard are positioned parallel to the quay. The stack blocks in the yard are accessible through the yard roads, which in turn are connected by perpendicular running highways.

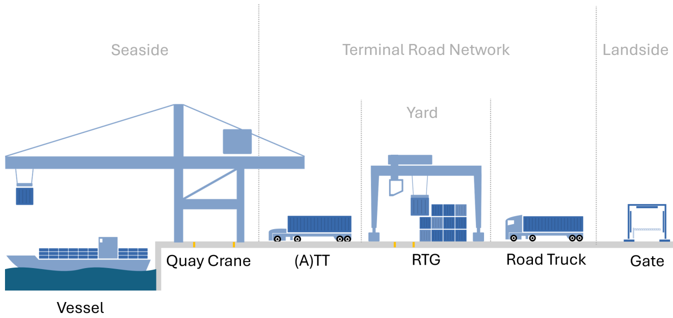


Figure 2. Schematic of a container terminal with parallel layout and RTGs

These highways then connect to the apron and the quay road on the seaside, and the back-road and gate on the landside (Notteboom, Pallis, and Rodrigue, 2021).
The HDVs which operate on the chosen terminal consist out of: road trucks, RTGs and QCs. The only autonomous vehicles which operate within this system are ATTs. The horizontal transport of containers is facilitated by ATTs for container moves within the terminal, and by road trucks for the horizontal transport of containers entering or leaving the terminal by road. RTGs are used to move containers between horizontal transport vehicles and the yard stacks, and QCs are used to move containers between the vessel and (A)TTs. As can be seen in the schematic of Figure 2.
Within the scope of this paper, four operational processes which occur on an RTG-based terminal were taken into account. The process of moving a container from the vessel into a stack block, and vice-versa, using a QC, an (A)TT and a RTG. As well as, the process of moving a container from the gate into a stack block, and vice-versa, using a road truck and a RTG (Gupta et al., 2017).
In terms of operational performance measurements of container terminals, the most relevant one for terminal operators is found to be the container throughput of the terminal, measured in TEU or containers in a given time horizon (Ports and Harbors, 2016). Further categorisations within container throughput, like TEU per QC or TEU per RTG could also be used.

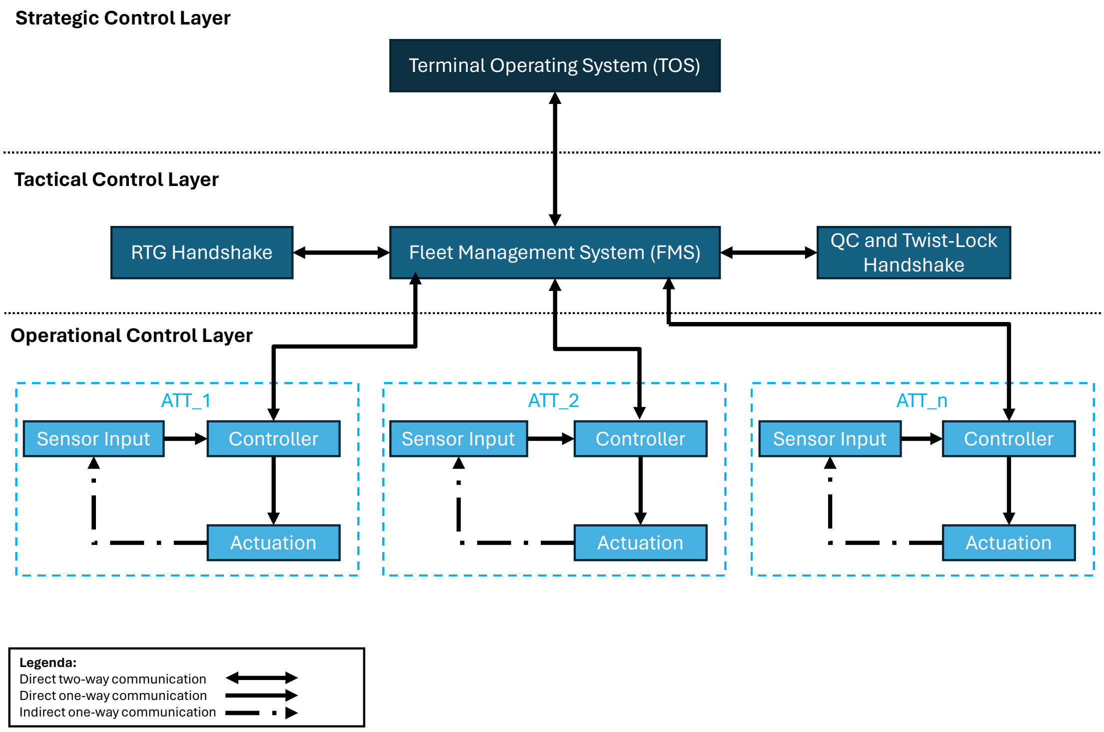


Figure 3. Control structure of a system of ATTs

ATT	LiDAR	Camera	(mm Wave) Radar	Ultrasonic	Other sensor
EasyMile (EasyMile, 2023)	Yes	Yes	Yes	No	GNSS, IMU and Odometry
Westwell/Qomolo (Westwell, 2022)	Yes	Yes	Yes	Yes	GPS & 5G Receiver
AI Drivers (AI-Drivers, 2023)	2	5	4	No	No
Gaussin (Gaussin, 2023)	Yes	Yes	Yes	No	No
Senior/Si Nian Zhijia (Senior, 2023)	Yes	Yes	No	No	No
ASI/Phantom Auto (ASI, 2023)	Yes	Yes	Yes	No	No
Embotech (Embotech, 2023)	3	4	1	1	INS and Visual Odometry

Table 1. Table summarising the available information about sensors on ATTs per manufacturer, with Yes/No indicating the presence of a sensor without a specified amount

4. System Analysis | ATT

Autonomous terminal tractors are currently being developed as a driver-less alternative to terminal tractors and a more flexible alternative to AGVs. There are several ATT developers currently in various phases from prototype testing to the first full fleet operations at container terminals. The main distinctive feature of ATTs is that they could be used in a AV-HDV mixed terminal environment. This way ATTs could drive in traffic between human driven road trucks in a RTG based terminal. To perceive other non-ATT vehicles around them, they utilise a set of sensors. The base components of this sensor set are mostly the same across ATT developers, and almost always consist out of at least a LiDAR, Camera and Radar. An overview of these is given in Table 1. The signals coming from these sensors are combined in a process called sensor fusion, to combine the strengths and mitigate the weaknesses of each sensor (Yeong et al., 2021).

ATTs in a container terminal operate within a multi-agent multi-layer control structure (Negenborn and Hellendoorn, 2010). At the strategic control layer there is the terminal operating system, which is in charge of the planning of container placement and vehicle assignment to jobs. In the layer beneath, the tactical control layer, the fleet management system is responsible for the routing of vehicles, facilitating the inter vehicle communication and intersection management. At the lowest layer, the operational control layer, lie the vision and actuation module of each ATT. For this paper it is assumed that ATTs can not directly communicate with each other, so there is a decentralised control structure (Westwell, 2022). This control structure is visualised in Figure 3

ATTs have various interaction points with the other vehicles on the terminal. They have an overlapping part of their operational area with the road trucks, so at any point on the terminal road network within this area overlap, interactions between the two could occur. Everywhere within their operational area, ATTs could have interactions with ATTs. ATTs also have interactions with RTGs and QCs whenever there are containers loaded or unloaded from the trailer of the ATT.

The intersections with which the ATTs interact come in two different forms. There are the ATT-only intersections and the mixed-traffic intersections. The ATT-only intersections are situated on the intersections of the apron and the highways, and as the name suggests, are only ATTs supposed to use these intersections. As these only serve autonomous vehicles, an intersection management system and conflict detection can be used to coordinate ATTs on these intersections. The layout of such an intersection can be found in Appendix Figure 9.

5. Literature Study

There is currently not a lot of literature available on ATTs, as they are still quite a recent development (Gerrits, Mes, and Schuur, 2020). In this section all relevant literature concerning ATTs is discussed, as well as literature on intersection strategies of (C)AVs and AGVs. The position of this study with respect to the existing literature is also discussed.

5.1 ATTs in mixed traffic container terminals

Gerrits and Schuur, 2022 and Gerrits et al., 2019 explain the basics of how one could implement ATTs with regards to intelligent decision making from the vehicle, and how these vehicles could theoretically interact with HDVs and equipment on the terminal. They propose a self-organizing multi-agent system where all ATTs can make their own routing and movement decisions. Gerrits, Mes, and Schuur, 2020 then went further in depth by simulating these ATTs in a mixed-traffic container terminal environment using the discrete-event simulation tool Siemens Plant Simulation. Here ATTs interacted with road trucks, RTGs and quay cranes. The field-of-view of the ATT has been modeled as one single 180 degree front facing LiDAR, and the ATT is programmed to slow down and/or stop when this sensor detects other vehicles, obstacles or workers. Experimentation with the number of deployed ATTs in the terminal saw higher congestion and ATT waiting times, but also higher QC utilisation rates with increasing numbers of deployed ATTs. Most of the available ATT literature has focused on what kind of traffic rules should apply at intersections where road trucks and ATTs mix. Horst, 2019 has found that if priority is given to road trucks, then the dwell times of these road trucks will reduce and subsequently the crowdednes and congestion would be reduced as well. Chen, Xu, and Wang, 2023 propose to make the priority strategy at junctions dynamic, with priority shifting between road trucks and ATTs, dependant on the amount of road trucks that are present on the terminal. Ng, Ong, and Zhou, 2022 agree with that, and also propose that turning and priority policies should depend on the ratio of ATTs to road trucks. Next to that they also propose that at high ATT to road truck ratios, there should be dedicated lanes for ATTs to drive on. Both Chen, Xu, and Wang, 2023 and Ng, Ong, and Zhou, 2022 however note that such dynamic priority strategies have only been tested in simulations, and as such are only more efficient in theory. It is still unknown how road truck drivers would react to such dynamic policies.

5.2 Intersection Strategies for (Connected) AVs

There have been numerous studies on intersection strategies specific for CAVs. Gholamhosseinian and Seitz, 2022 have reviewed 278 papers on this topic alone. They found that safety was by far the most researched topic for CAV intersections, followed by intersection efficiency. Nearly all studies utilised an optimization based coordination method for the intersection and trajectory planning as a method to check for conflicts at the intersection. There was a larger mix in architecture type between studies, with approximately 50% using a Vehicle-to-Vehicle (V2V) architecture, 40% a Vehicle-to-Infrastructure (V2I) architecture and 10% using both V2V and V2I.

Dresner and Stone, 2008 have proposed one of the first CAV intersection strategies with a First Come First Serve (FCFS) policy, using a spatio-temporal reservation grid in order to regulate a collision free vehicle flow on the intersection. They found that this intersection strategy vastly improves the throughput of a fleet of fully autonomous vehicles at the intersection when compared with traffic lights. The improvements are however largely diminished when HDVs make use of the same intersection. To mix the AVs and HDVs at the intersection, they have used a traffic lights which interact with the FCFS system.

Li and Liu, 2020 have proposed a low computational extension to the non-mixed FCFS strategy, incorporating a set conflict matrix and tested its efficiency against traditional and adaptive traffic lights. This matrix gives an overview of which origin-destination routes at the intersection conflict with each other. The intersection management system then checks using the matrix if approaching CAVs have a conflicts with each others route at the intersection. This intersection strategy is tested to be about as efficient as the original FCFS strategy of Dresner and Stone, 2008, but with a much lower computational burden on the central intersection management system.

Worrawichaipat et al., 2021 have proposed a FCFS strategy with a lower computational burden for the central intersection manager by incorporating a mix of V2V and V2I. Here the driver agents of the CAVs themselves do the path prediction and collision avoidance locally based upon a reservation map they receive from the central intersection agent. They then request access to the intersection from the central intersection agent based upon their predicted path. The central intersection agent here only regulates these reservations. It is tested against a traffic light scenario and the traditional FCFS strategy, and is found to be as approximately as efficient as the latter.

Chouhan and Banda, 2018 have proposed a three step heuristic for the scheduling at non-mixed intersections with a First-Enter-First-Serve strategy, which differs with the FCFS strategy by incorporating the approaching velocity of vehicles and how quickly these vehicles would clear the intersection, into its scheduling decision making process. The proposed First-Enter-First-Serve strategy is however not completely collision free, with the two other steps in the heuristic, a window scheduling and a reservation scheme, covering this weakness in the First-Enter-First-Serve strategy. This strategy is tested to have a higher throughput than the FCFS strategy at high traffic densities.

Liu et al., 2019 have proposed a cooperative scheduling mechanism for CAVs at a non-mixed intersection. This mechanism is not based upon the FCFS strategy of Dresner and Stone, 2008, but uses a different strategy that minimises the average waiting time of CAVs at the intersection. They utilise spatio-temporal reservation to detect conflicts between routes, and a window search method to determine the optimal schedule for vehicle movements on the intersection. This has been tested against traditional and adaptive traffic lights, and shows to have a significantly larger throughput than both.

It is worth noting that all mentioned papers on CAV intersections, have only tested their intersection strategies on a model of just the intersection alone, and these intersections are based upon intersections found on public roads. This does make the outcomes of these studies very accurate on the efficiency of the intersection, but gives little insight in how these intersections would impact a larger road network with multiple of these intersections. Li and Liu, 2020 and Liu et al., 2019 both included recommendations to test their strategy in an actual road network.

5.3 Intersection Strategies for AGVs

AGVs in container terminals have been the subject of many studies over the last few years. However most research has been in the direction of routing and scheduling strategies, with others also focusing on collision and deadlock prevention (Carlo, Vis, and Roodbergen, 2014). AGVs in container terminals generally do not utilise traditional intersections like those on public roads or RTG based terminals. The seaside of an AGV based terminal has mostly a perpendicular layout, which has no highways intersecting on the apron. Because of this, AGV based research is less relevant for this thesis with respect to intersections. However, the way AGVs solve claiming conflicts does draw similarities to how conflicts at ATT-only intersections could be solved as well.

Similar to CAVs, the FCFS strategy has also been widely used to solve AGV claiming conflicts, and also similar to CAVs, there have been numerous strategies which have been proposed to be better than the FCFS strategy.

Chan, 2022 has proposed a conflict resolution module using CPLEX and mixed integer programming, to find the optimal conflict resolutions in AGV schedules, both with and without giving weighted priorities to AGVs. The conflict resolution module proved slightly but noticeably more efficient than the FCFS strategy, with respect to QC productivity. Adding the weighted priorities did not have a significant impact.

Zheng et al., 2022 have proposed an adaptive learning algorithm to generate a optimal policy for dynamic AGV scheduling. They have tested their algorithm against the FCFS strategy and found it gave a significant improvement of QC productivity over the FCFS strategy.

5.4 Contributions of this Study

The research on ATTs in an RTG-based terminal is limited to their interactions at mixed ATT-road truck intersections and their general performance in simulations. There presently are no ATT based studies centered around intersection strategies for ATT-only intersections.

There have been numerous studies on CAV-only intersections, though these are mainly limited experiments with one isolated intersection, and never use the layout of a RTG-based terminal. There have aslo been numerous studies about conflict resolution of AGVs in container terminals, but they typically do not use the same type of intersections as present on an RTG-based terminal.

There is thus a research gap on how intersection strategies for ATT-only intersections could influence the productivity of the RTG-based terminal which they are implemented in. The goal of this study is to fill this gap, by conducting experiments with a simulation model of an ATT fleet on a RTG-based terminal and measuring which impact changing the intersection strategy of ATT-only intersections has on the productivity of QCs within the terminal.

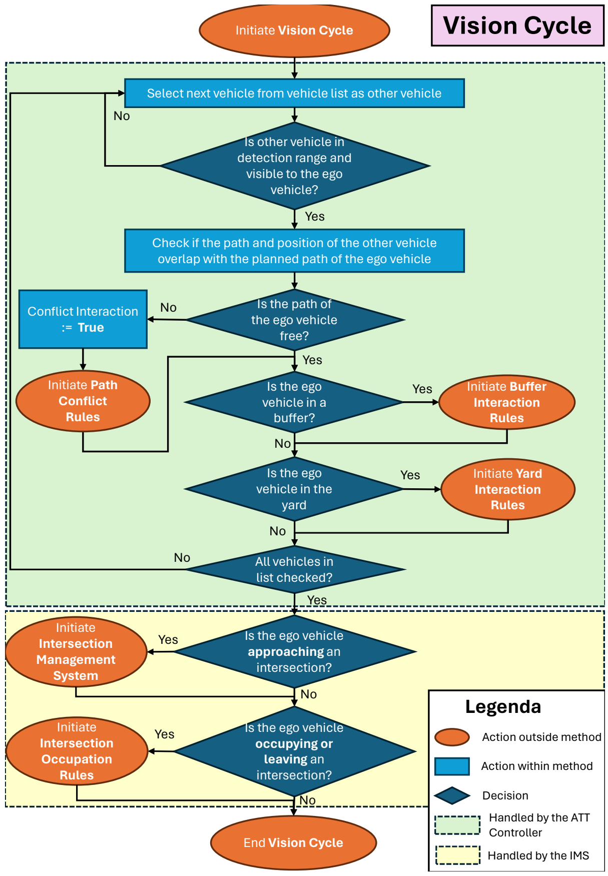


Figure 4. Flowchart of the designed ATT controller vision logic

6. Modelling

There are four systems of which models were included within this study: the RTG-based terminal, the ATT, the ATT controller and the intersection management system (IMS).

6.1 Model of the RTG-Based Terminal

The model of the RTG-based terminal has been developed and validated by Portwise, as a test terminal for new vehicle models for their simulations. It already has all needed features implemented on it to function as a standalone terminal model. It follows the layout of a basic parallel RTG-based terminal.

6.2 Model of the ATT

The model of the ATT is based on the existing TT model of Portwise, here a few input values have been changed to reflect the performance of a real-life ATT development. Next to that, the TT model will need some additional features, included in an ATT controller model to be able to function as an ATT model. These features include: a vehicle detection system akin to the sensors on the ATT and a rule-based actuation system which translates inputs from sensors and IMS into actions for the ATT.

6.3 Model of the ATT Controller

The model of the ATT controller has been developed especially for this study, to represent how a real-life ATT controller could function. It includes a main decision making logic, which uses the perception of the ATT, the overlap of its path with other vehicles and their paths, and the location of the ATT in relation the infrastructure, to determine its decisions with regard to actuation. This is coordinated by three sets of rules within the ATT controller model: the path conflict-, buffer interaction- and yard interaction rules. A flow chart visualising the main decision making logic can be found in Figure 4.

All major equations of the controller have been derived from the collision-free minimum safety distance equation for linear vehicle following of Shalev-Shwartz, Shammah, and Shashua, 2017, in Equation (1). This equation has been adapted to work for all other orientations of the other vehicle interacting with the ego vehicle, by adding $cos(rad_{ego} - rad_{other})$ for the term taking into account the speed and deceleration of the other vehicle, in Equation (2). This equation has also been verified by an ATT developer as approaching the same outcomes for the minimum safety distance as the calculations behind their own ATT development in real life.

$$d_{min} = v_{ego} * t_{reaction} + \frac{acc_{ego} * t_{reaction}^2}{2} + \frac{(v_{ego} + acc_{ego} * t_{reaction})^2}{2 * dec_{ego}} - \frac{v_{lead}^2}{2 * dec_{lead}} \quad (1)$$

$$d_{min} = v_{ego} * t_{reaction} + \frac{acc_{ego} * t_{reaction}^2}{2} + \frac{(v_{ego} + acc_{ego} * t_{reaction})^2}{2 * dec_{ego}} - cos(rad_{ego} - rad_{other}) \frac{v_{other}^2}{2 * dec_{other}} \quad (2)$$

Where d_{min} is the minimum safety distance between the ego vehicle and the other vehicle, v_{ego} is the current speed of the ego vehicle, $t_{reaction}$ is the reaction time between sensing the other vehicle and braking, acc_{ego} is the acceleration rate of the ego vehicle, dec_{ego} is the deceleration rate of the ego vehicle, v_{lead} is the current speed of the other (leading) vehicle and dec_{lead} is the maximum deceleration rate of the other (leading) vehicle.

6.4 Model of the Intersection Management System

The model of the IMS has also been developed especially for this study, and represents how such a system could function in a real life RTG-based terminal environment. This system coordinates the access of the ATTs to the ATT-only intersections. It does this by utilising an entry-and exit check to determine if an ATT can cross the intersection without stopping.

Dependant on the intersection strategy, it also utilises a matrix-check using a conflict matrix (Li and Liu, 2020), to determine if multiple vehicles can safely enter the intersection together. The conflict matrix has been visualised in Figure 5 and is based upon the implemented possible routes of ATTs at the intersection, visualised in Figure 6. In the conflict matrix, 0 represents that there is no conflict between the two routes and that vehicles could utilise both routes simultaneously. 1 represents that these are the same route, as such two vehicles can not take this route at the same time, but they can however take the intersection directly after each-other. 2 represents that there is a direct collision-causing conflict between the two routes. In this case the second vehicle should wait until the first has completely cleared the intersection before it could safely engage the intersection itself.

	A1L -A1R	A2L - A2R	A2L - H3	A2L - H4	A3R - A3L	A4R - A4L	A4R - H3	A4R - H4	H1 - A3L	H1 - A4L	H2 - A1R	H2 - A2R
A1L -A1R	1	0	2	2	0	0	0	0	0	0	2	0
A2L - A2R	0	1	1	1	0	0	0	0	0	0	2	2
A2L - H3	2	1	1	1	2	2	2	2	2	0	2	2
A2L - H4	2	1	1	1	2	2	2	2	0	0	2	2
A3R - A3L	0	0	2	2	1	0	2	2	2	0	2	2
A4R - A4L	0	0	2	2	0	1	1	1	2	2	2	2
A4R - H3	0	0	2	2	2	1	1	1	0	0	0	2
A4R - H4	0	0	2	2	2	1	1	1	0	0	0	0
H1 - A3L	0	0	2	0	2	2	0	0	1	1	2	2
H1 - A4L	0	0	0	0	0	2	0	0	1	1	2	2
H2 - A1R	2	2	2	2	2	2	0	0	2	2	1	1
H2 - A2R	0	2	2	2	2	2	2	0	2	2	1	1

Legenda	
0	No Conflict
1	Same Lane
2	Conflict

Figure 5. Conflict matrix of the Apron-Highway intersection

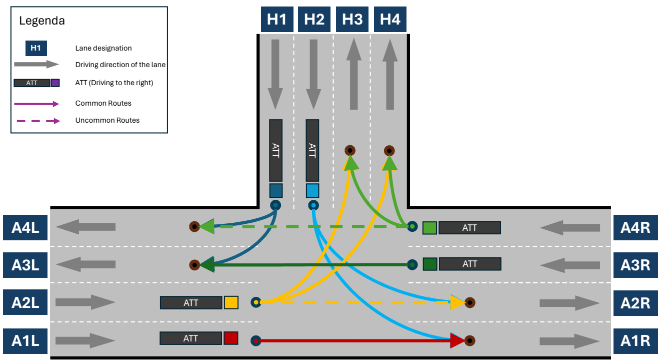


Figure 6. Possible routes of ATTs at an Apron-Highway Intersection

There have been four intersection strategies designed and included in the IMS:

- **One-Vehicle-at-a-Time First-Eligible-First-Serve (One-FEFS)**: Gives access to the next vehicle in queue at the intersection that can cross the intersection without stopping, with a limit of one vehicle at a time on the intersection.
- **Multiple-Vehicles-at-a-Time First-Eligible-First-Serve (Multi-FEFS)**: Gives access to the next vehicle in queue at the intersection that can cross the intersection without stopping and which does not conflict with vehicles which are already on the intersection, with no limit on the amount of vehicles on the intersection, based on the FCFS principle from Li and Liu, 2020.
- **QC Destination Priority (QC-Prio)**: Same as Multiple-Vehicles-at-a-Time FEFS, but registers vehicles to the front of the queue if they have a QC as their destination.
- **Priority for Delayed ATTs with QC Destination (Delay-Prio)**: Same as QC Destination Priority, but now an even higher priority is given to vehicles which have a QC as their destination and are delayed.

Flowcharts for the logic of these four strategies can be found in the Appendix, Figure 10 to Figure 13 respectively.

6.5 Verification and Validation

All models made for this thesis have been verified using code walkthroughs and traces, and have been validated through observing the animations produced by the simulation software, following the techniques of Sargent, 2010. An animation of two simulated hours, covering all basic functionalities of the model has been shown to industry experts from EasyMile and Portwise, in order to collect their feedback on the validity of it. It has also been observed over many real-life hours by the maker of the model, for multiple simulation runs featuring different container plannings, so the ATTs performed different routes in each run. There are still some discrepancies between the model of the ATT and ATT controller, and how they would function in real life, which have been noted during the validation process. A large part of this discrepancy could be solved in the future by including dynamic routing and pathing in the ATT model.

7. Experimental Setup

The model of the of the RTG-based terminal is configured with the values from Table 2, and the layout of the terminal is configured as is visible in Appendix Figure 14.

Input Parameter	Value	Unit
# of Stack Blocks	32	-
# of RTGs	64	-
# of QCs	10 (peak) & 5 (off-peak)	-
# of ATT-only Intersections	3	-
# of Yard-Highway Intersections	12	-
Road Truck Arrival Rate	20	Trucks per hour
Quay Length	1000	m
Terminal Depth	300	m

Table 2. Terminal configuration parameters

There are two sets of input parameters for the ATT model. The first set is specific for ATTs and the values for these are provided by an ATT developer, the other set is more for TTs in general and has been provided by Portwise. The values and parameters for these sets can be seen in Table 3 and Table 4 respectively.

Input Parameter	Value	Unit
Max. Straight Speed	6.945	m/s
Max. Speed in Turns	1.897	m/s
Acceleration Rate	1	m/s^2
Deceleration Rate	0.8	m/s^2
Emergency Deceleration Rate	2.8	m/s^2
Emergency Distance Trigger	9	m
Signal Response/Reaction Time	0.8	s
Detection Range	100	m
Viewing Angle	6.2	Radians

Table 3. ATT specific input parameters

Input Parameter	Value	Unit
Length Tractor	5	m
Width Tractor/Trailer	3	m
Length Trailer	14	m
Turning Radius	6	m

Table 4. General TT input parameters

A set of comparative tests is run with all designed intersection strategies as well as with the non-autonomous TT model of Portwise as a benchmark. These tests are performed to measure the influence of each intersection strategy on the productivity of the terminal and will be tested using both an peak-load and an off-peak-load scenario. In these scenarios, the amount of active QCs and (A)TT fleet sizes is given in Table 5. The set of off-peak-load configurations is chosen to correspond to the same comparable fleet size as the peak-load configurations, with both having the same amount of (A)TTs per QC.

Scenario	Active QCs	(A)TT Fleet Size		
Peak-Load	10	40	50	60
Off-Peak-Load	5	20	25	30

Table 5. Active QC and (A)TT fleet size configurations for peak-load and off-peak-load scenarios

8. Results & Discussion

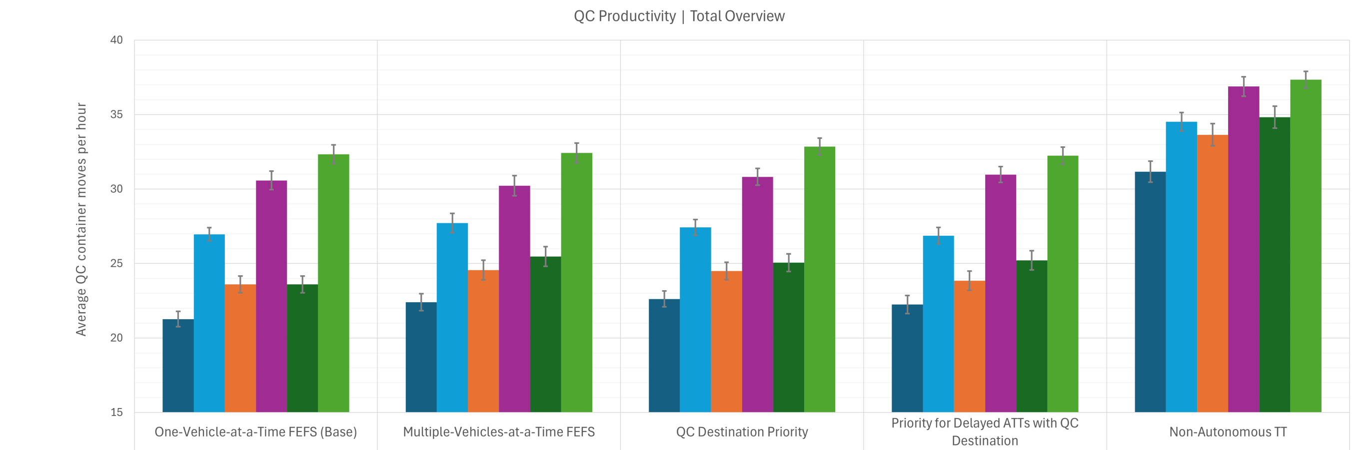
The results of the comparative tests are given in Figure 7, in terms of QC moves per hour, and in Figure 8, in terms of total number of intersection crossings performed by ATTs. The latter does not feature the benchmark test with the non-autonomous TTs, as these have no IMS to register intersection crossings in their model.

From the comparative tests of intersection strategies under the peak-load scenario, it was found that switching from a one-vehicle-at-a-time intersection strategy type to a multiple-vehicles-at-a-time one, will generally increase the QC productivity and intersection throughput with a significant margin ranging from 1 to 1.9 containers per hour. This was not really a surprising outcome, but does signal that the style of ATT-only intersection coordination does impact the overall terminal performance in this scenario. It was also found that utilising either the Multi-FEFS or the QC-Prio intersection strategy has lead to the best performances in terms of terminal productivity, with the former performing better at the higher ATT fleet sizes, and with no statistically significant differences found between the results of the two strategies. The Delay-Prio strategy did not perform best in any test, but only performed statistically significantly worse in the 50 ATT fleet configuration. In essence, has the difference between the tested intersection strategies little impact on the QC productivity under peak-load, as long as multiple vehicles are allowed on the intersection at once.

For the comparative tests with the off-peak-load scenario, it was found that the different ATT intersection strategies have little to no impact on the performance of the terminal when there is not a lot of traffic on the terminal road network, and there was not one intersection strategy which consistently outperformed the others. This is also not an surprising outcome, as there is less opportunity for congestion to happen near the intersections when there are less ATTs in a fleet. The QC-Prio strategy however did perform the most consistently well across the off-peak tests, with an average increase of 0.5 containers per hour in terms of QC productivity when compared to the One-FEFS strategy. As such, this strategy would be recommended to be used in this scenario.

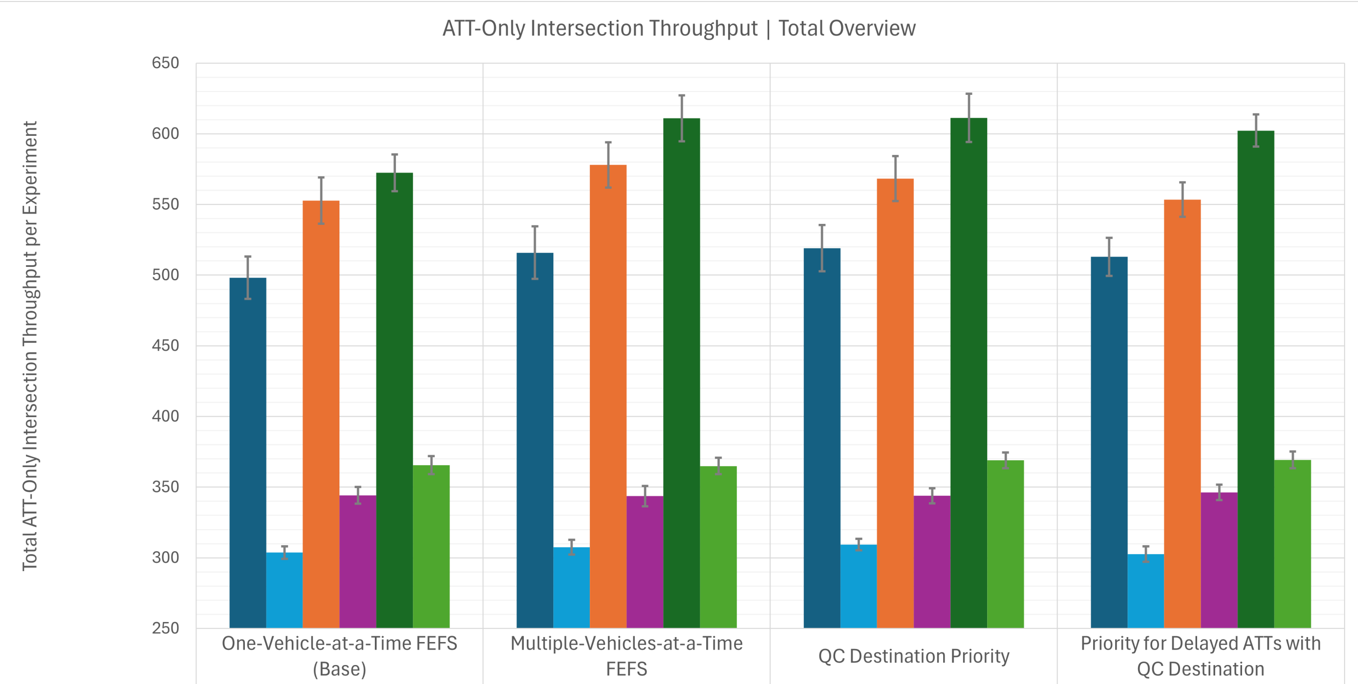
When comparing the peak-load and off-peak-load scenarios, it was found that the test of the off-peak scenario had a significantly higher QC productivity than the tests of the corresponding peak-load scenario, with an approximate gap ranging from 5 to 8 containers per hour, increasing with the fleet size. This difference in productivity could be attributed to higher levels of congestion during the peak scenario, and additionally it could be argued that the peak-load QC performances could approach their corresponding off-peak-load counterparts, when the congestion on the terminal road network would be eliminated. Through this comparison it could also be argued that congestion plays a large role in hampering the performance of the ATT model during a peak-load scenario.

In the end, all tested ATT configurations performed significantly worse than the non-autonomous TT model it was based upon. However the gap in performance was noticeably smaller for the off-peak-load scenario than for the peak-load one, with an average approximate gap of 6 containers per hour for the off-peak-load scenario and 9 containers per hour for the peak-load scenario. This is partially explained by the proneness of the ATT model to congestion, especially when utilising large fleet sizes. Possibly if dynamic pathing and routing will be implemented in a future iteration of the ATT model, the performance of it could approach the performance of the TT model. It should however be noted that ATTs by design will probably not outperform human driven TTs in real world operations either. For now at least, are the QC performance values from the ATT model results not yet a valid indication for the real-life performance which these vehicles could achieve, and should thus not be used for anything else than the comparison within this study.



	One-Vehicle-at-a-Time FEFS (Base)	Multiple-Vehicles-at-a-Time FEFS	QC Destination Priority	Priority for Delayed ATTs with QC Destination	Non-Autonomous TT
40 (A)TT	21.27	22.41	22.62	22.25	31.16
20(A)TT Off-Peak	26.96	27.72	27.42	26.87	34.52
50 (A)TT	23.60	24.56	24.50	23.84	33.65
25(A)TT Off-Peak	30.58	30.22	30.82	30.97	36.88
60 (A)TT	23.60	25.48	25.06	25.22	34.82
30(A)TT Off-Peak	32.33	32.42	32.85	32.24	37.34

Figure 7. Total overview of all QC productivity results for both the peak- and off-peak-load scenarios



	One-Vehicle-at-a-Time FEFS (Base)	Multiple-Vehicles-at-a-Time FEFS	QC Destination Priority	Priority for Delayed ATTs with QC Destination
40 (A)TT	498.08	515.87	519.08	512.90
20(A)TT Off-Peak	303.65	307.48	309.37	302.59
50 (A)TT	552.81	577.94	568.33	553.41
25(A)TT Off-Peak	344.17	343.64	343.86	346.28
60 (A)TT	572.45	610.93	611.17	602.21
30(A)TT Off-Peak	365.47	364.93	368.94	369.28

Figure 8. Total overview of all intersection throughput results for the peak- and off-peak-load scenarios

9. Conclusion

The aims of this study were to develop a model of an autonomous terminal tractor (ATT) within an existing discrete event simulation model of a rubber tired gantry (RTG)-based container terminal, and to use this model to research the influence of the intersection strategies in ATT-only intersections on the productivity of the RTG-based terminal. Within this study, three models have been developed and integrated into the terminal model, these are the: the ATT model, the ATT controller model and the intersection management system (IMS) model. Within the IMS model four different intersection strategies were developed: One-Vehicle-at-a-Time First-Eligible-First-Serve (One-FEFS), Multiple-Vehicles-at-a-Time FEFS (Multi-FEFS), Quay Crane (QC) Destination Priority (QC-Prio) and Priority for Delayed ATTs with QC Destination (Delay-Prio).

By conducting experiments with these developed models and intersection strategies, it was found that the degree of influence the strategy of an ATT-only intersection has on the productivity of an RTG-based terminal, is dependant on the ATT fleet size. Here the lower fleet sizes (20 to 30 ATTs), which were tested with the off-peak-load scenario, showed no significant differences in QC productivity between the different tested intersection strategies. While the higher fleet sizes (40 to 60 ATTs), which were tested with the peak-load scenario, did show a significant increase in QC performance ranging from 1 to 1.9 containers per hour, when going from a strategy where only one-vehicle-at-a-time was allowed on the intersection to a strategy where multiple-vehicles-at-a-time were allowed on the intersection.

As congestion was also observed to increase with fleet size, it shows that at smaller fleet sizes there are not enough ATTs which want to cross the same intersection at the same time, that changing intersection strategies has any significant effect on their performance within the terminal. At higher fleet sizes, ATT-only intersections become larger bottlenecks, hence the more influence changing the intersection strategy has on the overall terminal performance in these configurations. For the One-FEFS strategy, the QC performance even decreases slightly going from a 50 ATT to 60 ATT fleet, which is due to the added congestion these 10 extra vehicles produce.

As the less congested off-peak-load smaller fleets had a QC productivity which was 5 to 8 containers per hour higher than the peak-load larger fleets, while having the same amount of ATTs per QC, it can be concluded that congestion greatly hampers the terminal productivity, with the current ATT-model. The proposed intersection strategies only alleviate a part of this congestion, as its influence on the QC productivity is found to be less than 2 containers per hour.

In terms of best performing intersection strategies within this thesis, it has been found that the QC-Prio strategy performed the most consistently well across the fleet sizes in the off-peak-load scenario, with an average increase of 0.5 containers per hour in terms of QC productivity when compared to the One-FEFS strategy, though this is not a statistically significant difference. For the peak-load scenario, it has been found that the QC-prio scored best on the lower (40 ATT) fleet configuration test, with a QC productivity increase of 1.3 containers per hour. The Multi-FEFS strategy was found be the best performing strategy at the higher (60 ATT) fleet configuration test, with a QC productivity increase of 1.9 containers per hour.

10. Recommendations

For a further study in the realm of ATT simulations, the following recommendations are given:

1) **Develop strategies to ease congestion**
   Congestion in terminals operating with ATT-fleets, is still a unresearched topic. This while it has been observed to be a significant contributor to inefficiencies within the ATT-model. As ATTs could in theory be directed by the FMS to act in a way which minimises the congestion of the terminal as a whole, a sort of theoretical system optimal way of coordinating ATTs on a terminal could be researched. The influx of human driven road trucks onto the terminal, does make this system more complex to design. Though, one could design a system where the FMS knows the exact location of each road truck, through some sort of V2I type interaction. Simulating such a system should be significantly simpler than testing it in real-life, and through a simulation, it can be tested if such a system could minimise or even completely eradicate congestion on the terminal road network.
   Part of these strategies should be a dynamic routing and pathfinding module for the ATT model. The current model can not deviate from its originally given path, which propagates an unnecessary amount of congestion and deadlocks. Including a system which can detect if there is a less congested route possible by facilitating a lane change, can alleviate this issue.
2) **Develop a model using real-life operations**
   At the beginning of this thesis project (November 2023) there were only a handful of ATT concepts which have been tested in terminal operations, and mostly only in very small fleet configurations. As such, it is more difficult to model these ATT concepts, as there are only a limited amount of resources on their real-life behaviour in fleet. Within the coming years, ATTs will most likely be implemented in a much larger scale within some RTG-based terminals. This will be a perfect opportunity to develop a more realistic ATT

simulation model, as the behaviour of these vehicles can be observed in more detail and in more situations.

3) **Perform tests with varied road layouts** There have been no studies yet on how variations in the terminal road layout impact the efficiency of the terminal. In this thesis there has also only been one road layout used to perform all experiments with. Therefore it is not known what the impact would be on ATT based operations when lanes would change direction or when buffers would change location. It is possible that a more efficient road layout could be found or designed especially for interactions with ATTs. One possible design direction could be to dynamically change the lane directions for ATT-only lanes, dependant on the amount of ATTs that have a destination at the yard or QC.

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Appendix

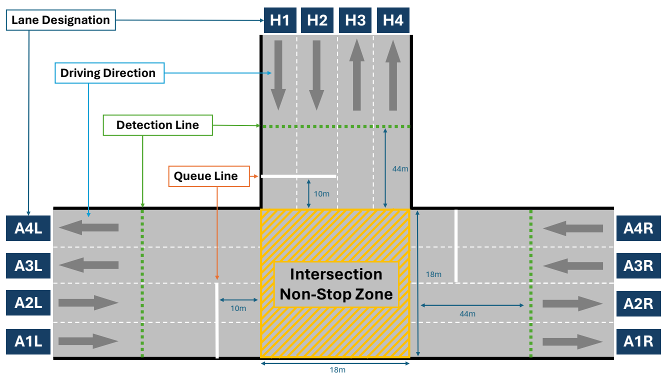

Figure 9. Layout of an Apron-Highway Intersection

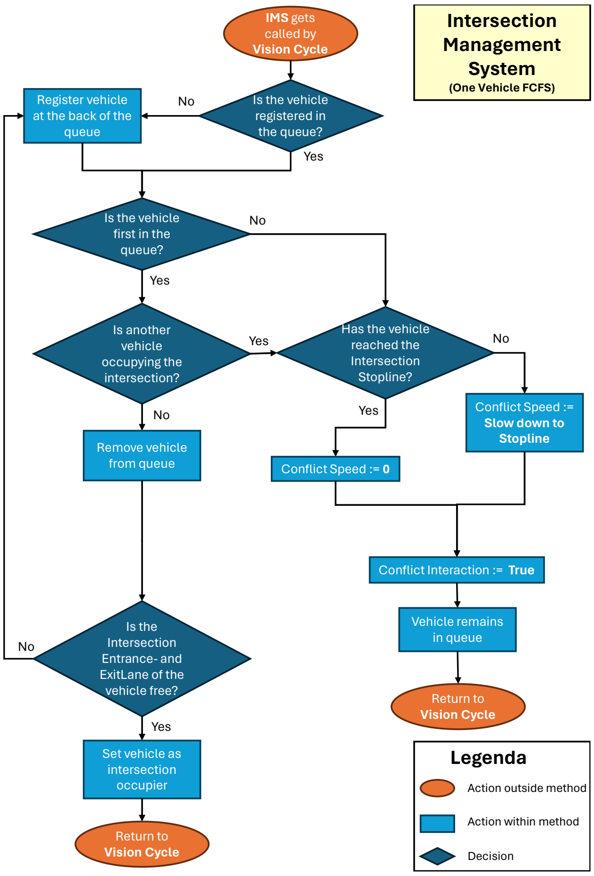

Figure 10. Flowchart of the One-FEFS strategy

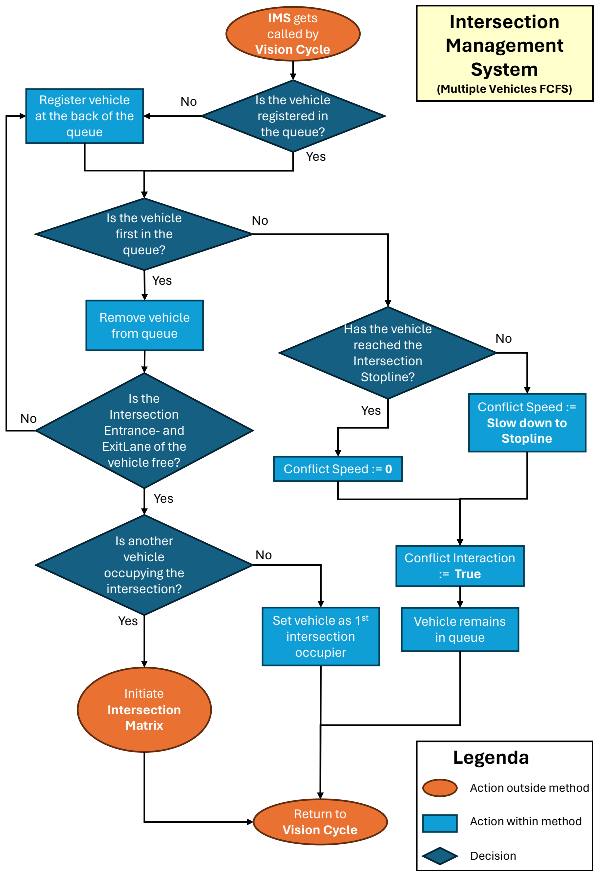

Figure 11. Flowchart of the Multi-FEFS strategy

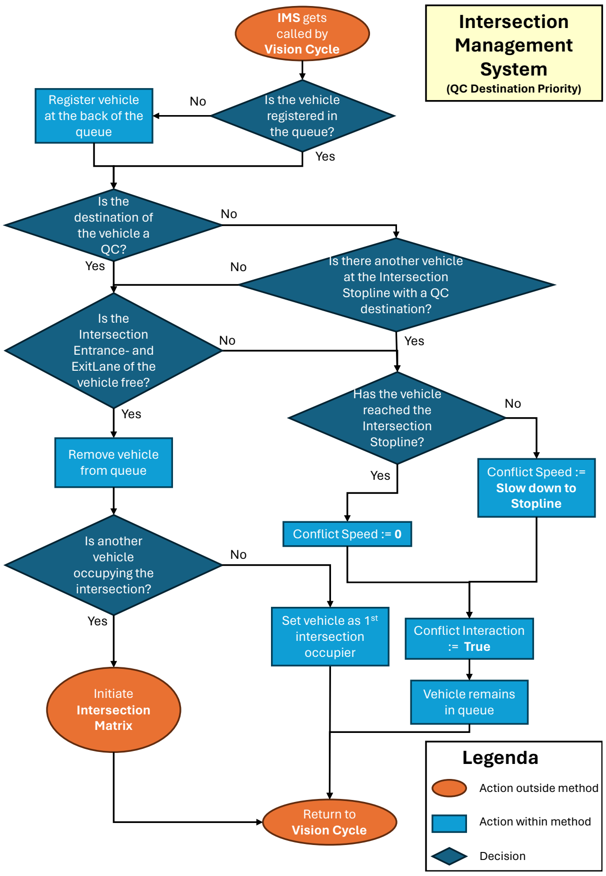

Figure 12. Flowchart of the QC-Prio strategy

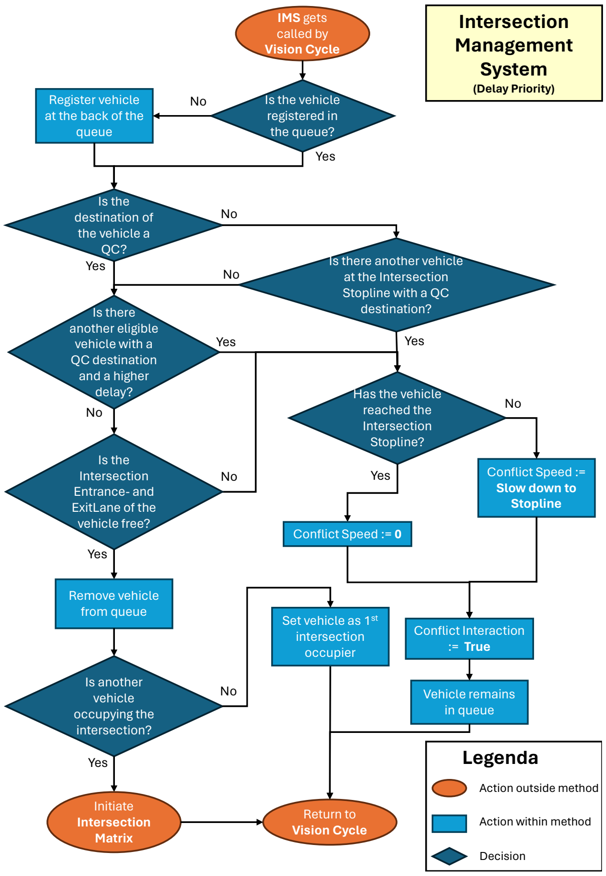

Figure 13. Flowchart of the Delay-Prio strategy

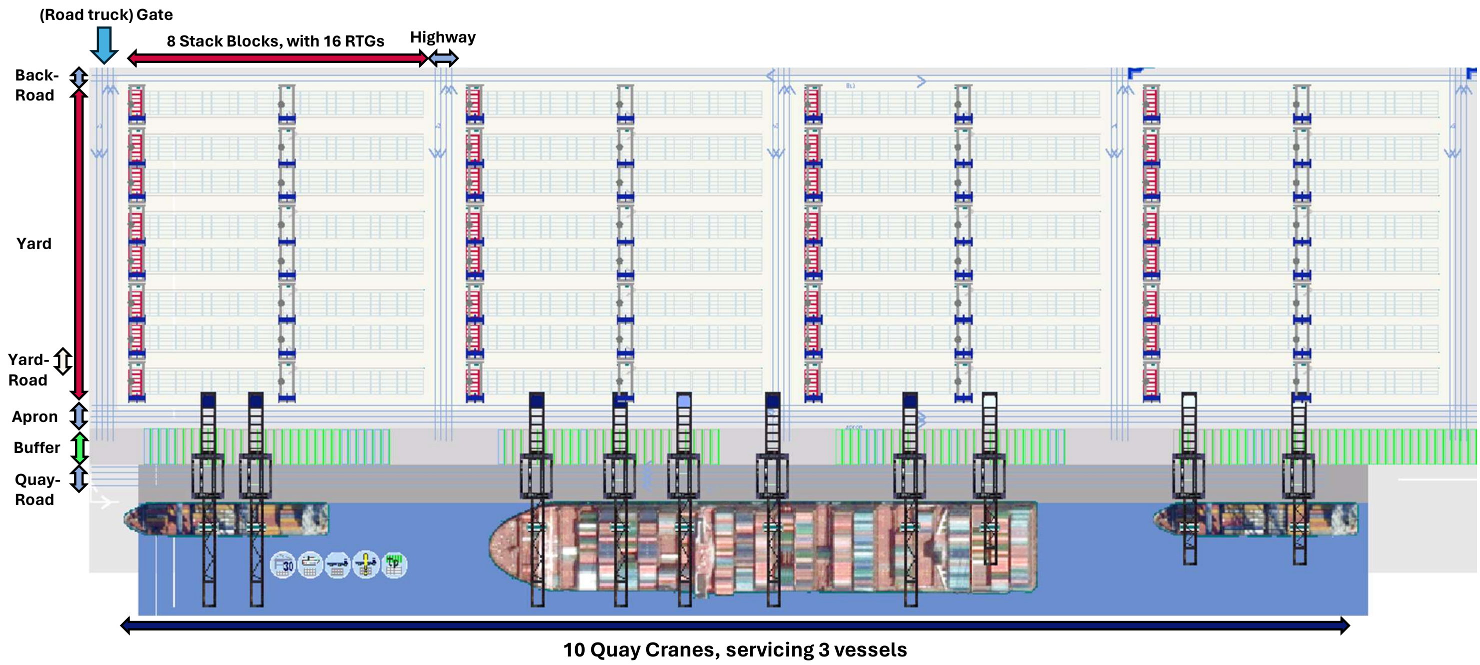

Figure 14. Visualisation of the layout of the test terminal

B

Additional Background Information

For the sake of readability, some sections have been relegated to the appendix. These have been listed in number of appearance in which they would have otherwise appeared in the main text.

B.1. Challenges During the Modelling Process

During the development of the modeling, some situations occurred which made the process of modelling take longer than anticipated.

B.1.1. Complex Apron-Buffer Interactions

The standard rules for checking if a turn is free do not always suffice for situations when an ATT wants to make a turn out of a buffer. Especially when two ATTs want to exit the buffer at the same time or when an ATT has to cross two apron lanes for it to reach its desired lane to turn into. This has lead to the development of the buffer interaction rules in Section 5.3.5. Another problematic scenario occurred around the buffers close to intersections, where the queuing rules of the intersections interfered with the exiting rules of the buffer. The solution here was to remove the buffers which were to close to the intersections.

B.1.2. Deadlocks

Deadlocks happen when two (or more) vehicles are in an unsolvable conflict interaction with each other. The source of these deadlocks were mostly flawed logic, especially at the intersections. Some other deadlocks came to be due to the infrastructure layout providing situations for which the logic was not initially planned to deal with. The largest problem with these deadlocks, was that the solving of the underlying logic issues was an iterative process. This was, because whenever logic was added or amended to solve one deadlock situation, other often new deadlock situations would arise.

In the finished model most deadlock situations have been cleared, though one type persists with the current logic. Here vehicles will queue in a circle around a stack block, as can be seen in Figure B.1. This is due to the ATTs only utilising static routing and thus not being able to change the path they take mid-route.

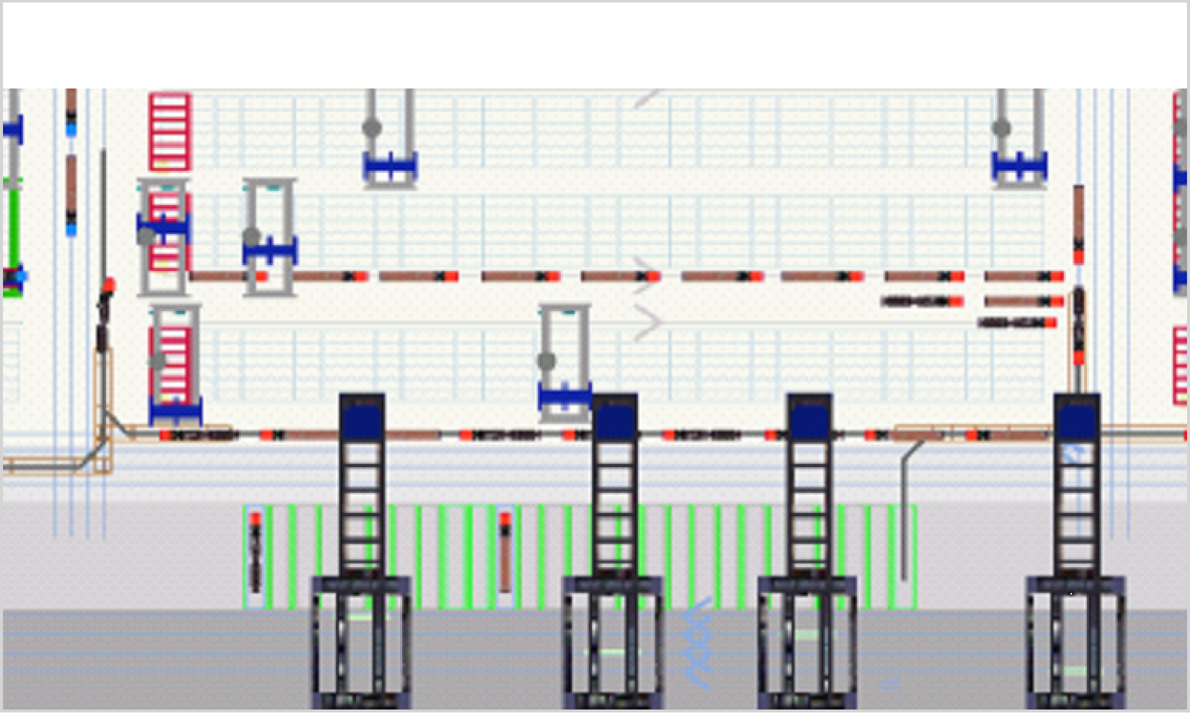

Figure B.1: ATTs in deadlock in a circle around a stack block

B.1.3. Road Truck Behaviour

The road truck model developed by Portwise was not made to drive exactly as drive road trucks in real life. There have been simplifications made within the congestion detection of this model. If a modeled road truck would encounter other non-moving vehicles which are blocking its route and are not queuing for the same stack as its destination, it would drive trough them. This is because in real life, truckers would find an unorthodox route around these vehicles wherever there is space, but modelling this exact behaviour is nearly impossible.

This behavioural design choice had a lot of impact on the model of the ATT which could not handle vehicles driving through each other or through themselves. To combat this, the road trucks were forced to utilised the same logic as the ATTs for vehicle detection and distance keeping rules.

B.1.4. Yard Road - Highway Intersections

The yard road to vertical highway intersections required a different rule-set than the intersections on the apron. These intersections have a slightly different layout than those at the apron, with three lane one-way yard roads having a cross intersection with a four lane two-way highway. At first these intersections were approached just as turns, where ATTs relied just on their sensors in order to check if the path is clear to engage on the intersection. It was however found that this lead to undesirable behaviour, like ATTs standing still on the intersection and blocking multiple lanes of traffic this way.

To solve this problem, these intersections were given a separate rule-set as well, where all vehicles exiting the yard lane had to carry out an extra check in order to detect vehicles approaching on the highway. ATTs exiting the yard road always have to give way to vehicles on the highway. This is what turned into the yard interaction rules in Section 5.3.6.

In addition, ATTs entering the yard road had to do an extra check to determine if they could do a non-stop turn into the yard road, as so they would not block the yard-highway intersection while turning. This rule has not been included into the flowchart of the yard interaction rules, but is built into the ATT controller model.

B.1.5. Debugging

A lot of time (around 2 months of full time work) has been spent on debugging the simulation code of the model. Bugs and faults in the implementation have been found in nearly all aspects of the ATT model, and systematically diagnosing where the roots of these faults were located, was a large part of this time investment. A part of these were faulty implementations of the designed ATT model or noticing that certain designed aspects did not work as intended in the actual simulation environment. An other part were difficulties of integrating the ATT model with the established terminal in TIMESQUARE, as a lot of its systems were designed for the TT model which used a different more centralised way to coordinate the terminal. Changing this to the decentralised structure of the ATTs, broke a lot of the pre-existing rules between the TTs, RTGs and QCs.

In the initial panning of this thesis, no time was planned for this debugging process. A takeaway from this all is that implementation of a simulation model with autonomous vehicles will take longer than you will initially think it will, as there will be situations which can occur which you will initially not have thought off. It will also take a lot of time to implement a new model into an already existing simulation environment.

B.2. Extra Information on the Results Section

B.2.1. Result Data of All Replications

B.2.2. Problematic Situations in Replications

Replication Statistics Not all experiments have the same amount of replications. The difference in these amounts is attributable to two different causes. One is that some experimental setups were way more prone to running into the aforementioned problematic situations causing deadlocks or the simulation to run very slowly. For the very slow running simulations, it was chosen to limit the amount of replications for the sake of time management.

The second cause, is that some experiments needed some extra replications in order to meet the requirement of the confidence interval wideness.

B.3. Additional Result Visualisations and T-test P-values

Here the visualisations and T-test matrices are ordered per fleet size. In the T-test matrices, the P-values < 0.05 indicate a significant difference between two sets of results, which are indicated in green.

B.3.1. 40 (A)TT Fleet Configuration

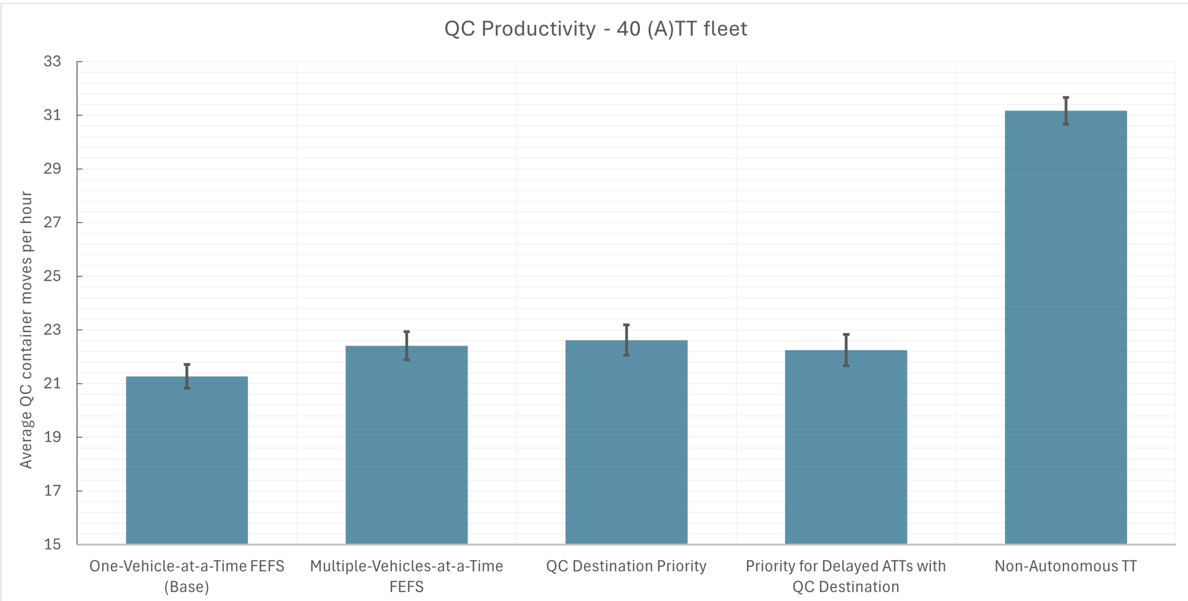

Figure B.2: QC productivity results for 40 (A)TT fleet configuration test in peak-load scenario

QC Productivity | 40 (A)TT Peak-Load					
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio	Non-Autonomous TT
One-FEFS	1	-	-	-	-
Multi-FEFS	0.001224567	1	-	-	-
QC-Prio	0.000254989	0.575076219	1	-	-
Delay-Prio	0.008113203	0.682887836	0.3538401	1	-
Non-Autonomous TT	4.60728E-40	2.48174E-35	8.3943E-35	4.74713E-38	1

Figure B.3: P-value matrix of the QC productivity results for 40 (A)TT fleet configuration test in peak-load scenario

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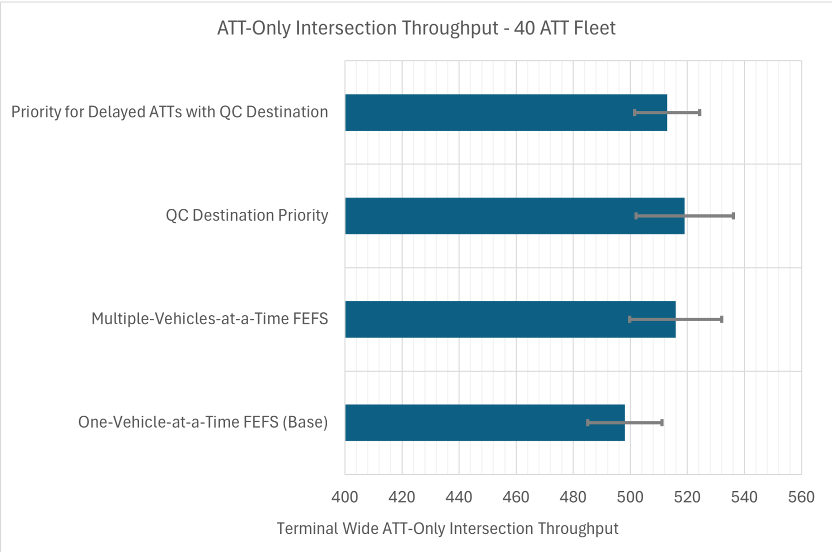

Figure B.4: Intersection throughput results for 40 (A)TT fleet configuration test in peak-load scenario

Intersection Throughput | 40 (A)TT Peak-Load				
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio
One-FEFS	1	-	-	-
Multi-FEFS	0.084120825	1	-	-
QC-Prio	0.049894759	0.779733143	1	-
Delay-Prio	0.08648464	0.760468498	0.54166441	1

Figure B.5: P-value matrix of the Intersection throughput results for 40 (A)TT fleet configuration test in peak-load scenario

Return to main text Section 7.1.1

B.3.2. 50 (A)TT Fleet Configuration

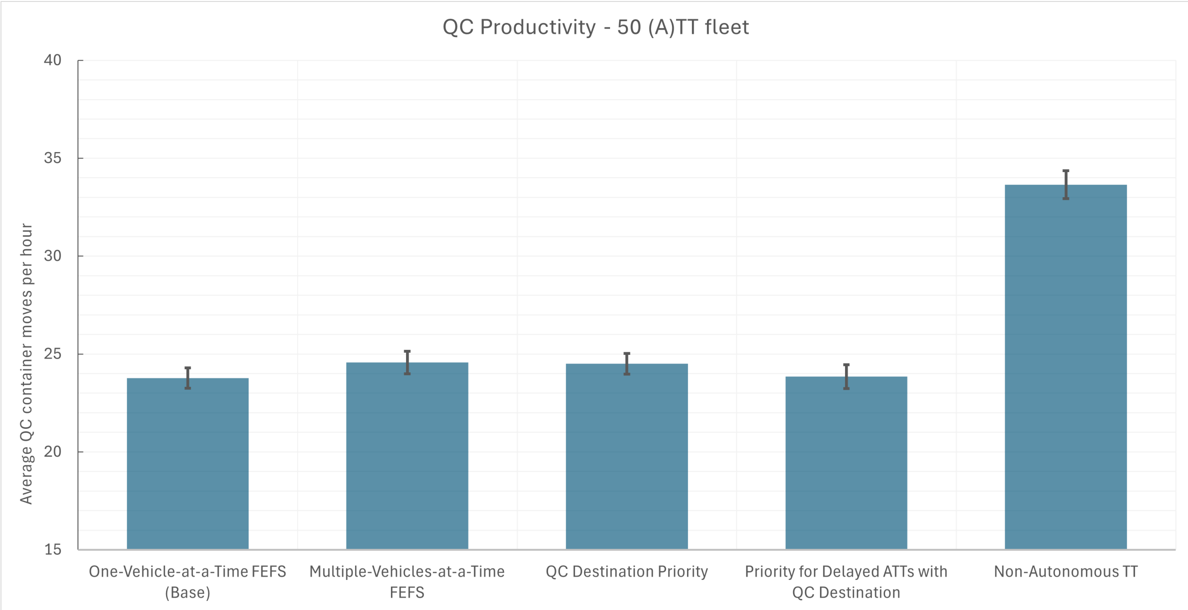

Figure B.6: QC productivity results for 50 (A)TT fleet configuration test in peak-load scenario

	QC Productivity | 50 (A)TT Peak-Load				
	One-FEFS	**Multi-FEFS**	**QC-Prio**	**Delay-Prio**	**Non-Autonomous TT**
One-FEFS	1	-	-	-	-
Multi-FEFS	0.040045021	1	-	-	-
QC-Prio	0.050465873	0.878498946	1	-	-
Delay-Prio	0.84269425	0.087776654	0.108833713	1	-
Non-Autonomous TT	3.30258E-29	7.31258E-29	3.27319E-29	1.37724E-30	1

Figure B.7: P-value matrix of the QC productivity results for 50 (A)TT fleet configuration test in peak-load scenario

Return to main text Section 7.1.1

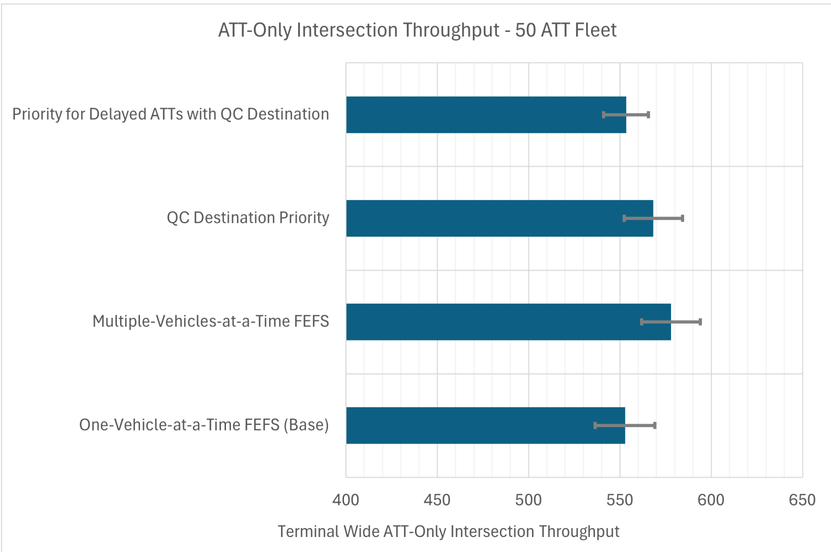

Figure B.8: Intersection throughput results for 50 (A)TT fleet configuration test in peak-load scenario

Intersection Throughput | 50 (A)TT Peak-Load				
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio
One-FEFS	1	-	-	-
Multi-FEFS	0.028048035	1	-	-
QC-Prio	0.167124614	0.390487244	1	-
Delay-Prio	0.951764622	0.016462792	0.137636309	1

Figure B.9: P-value matrix of the Intersection throughput results for 50 (A)TT fleet configuration test in peak-load scenario

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B.3.3. 60 (A)TT Fleet Configuration

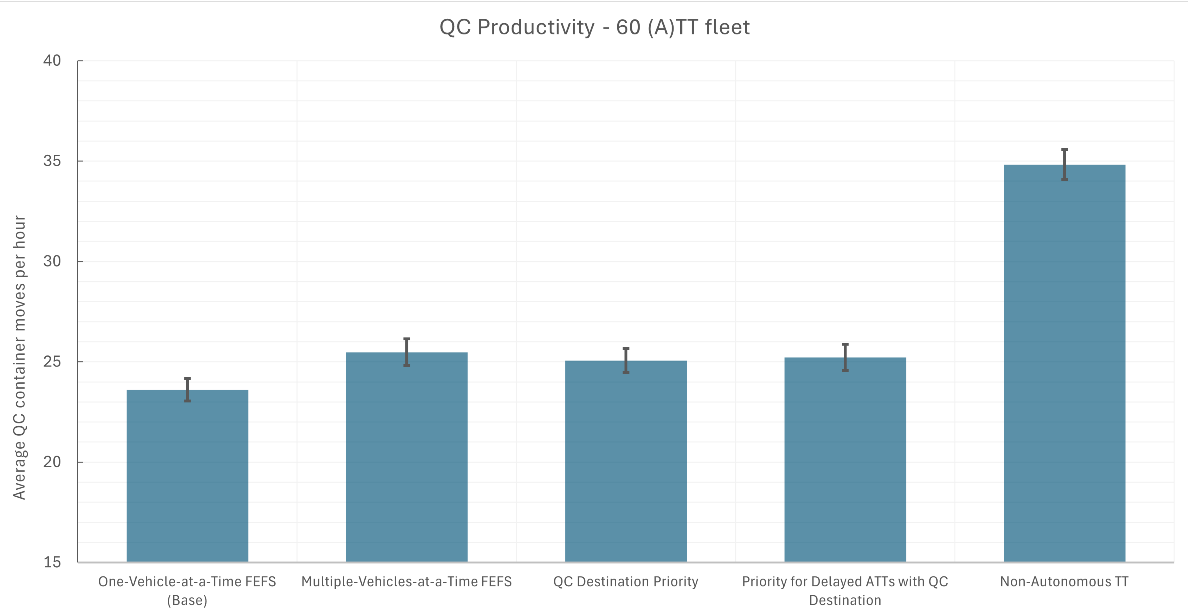

Figure B.10: QC productivity results for 60 (A)TT fleet configuration test in peak-load scenario

QC Productivity | 60 (A)TT Peak-Load					
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio	Non-Autonomous TT
One-FEFS	1	-	-	-	-
Multi-FEFS	3.3876E-05	1	-	-	-
QC-Prio	0.000512833	0.342916652	1	-	-
Delay-Prio	0.000265208	0.573994413	0.712206423	1	-
Non-Autonomous TT	1.94395E-36	1.95883E-31	4.20476E-33	1.54534E-31	1

Figure B.11: P-value matrix of the QC productivity results for 60 (A)TT fleet configuration test in peak-load scenario

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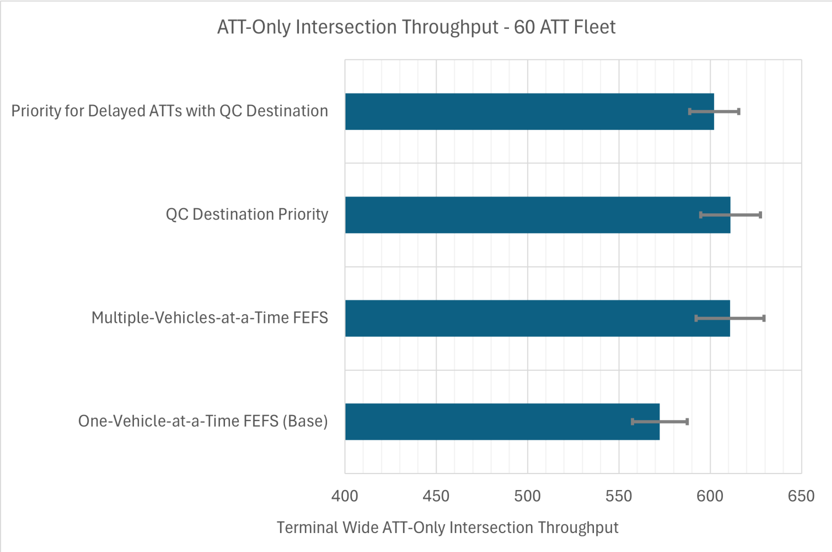

Figure B.12: Intersection throughput results for 60 (A)TT fleet configuration test in peak-load scenario

Intersection Throughput | 60 (A)TT Peak-Load				
	One-FEFS	**Multi-FEFS**	**QC-Prio**	**Delay-Prio**
One-FEFS	1	-	-	-
Multi-FEFS	0.001688536	1	-	-
QC-Prio	0.000735763	0.983833544	1	-
Delay-Prio	0.003822092	0.44350242	0.395121523	1

Figure B.13: P-value matrix of the Intersection throughput results for 60 (A)TT fleet configuration test in peak-load scenario

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B.3.4. 20 (A)TT Fleet Configuration | Off-Peak

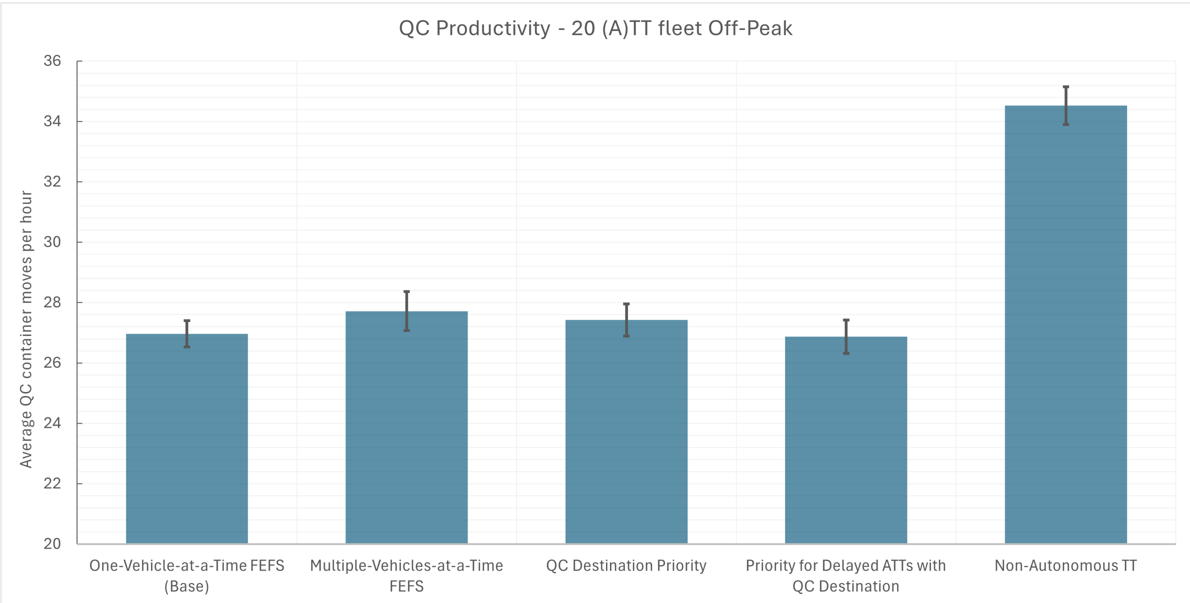

Figure B.14: QC productivity results for 20 (A)TT fleet configuration test in off-peak-load scenario

QC Productivity | 20 (A)TT Off- Peak-Load					
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio	Non-Autonomous TT
One-FEFS	1	-	-	-	-
Multi-FEFS	0.057274194	1	-	-	-
QC-Prio	0.185387348	0.485323757	1	-	-
Delay-Prio	0.790244835	0.04935439	0.151906396	1	-
Non-Autonomous TT	9.76713E-28	2.31453E-25	5.17522E-27	1.02529E-28	1

Figure B.15: P-value matrix of the QC productivity results for 20 (A)TT fleet configuration test in off-peak-load scenario

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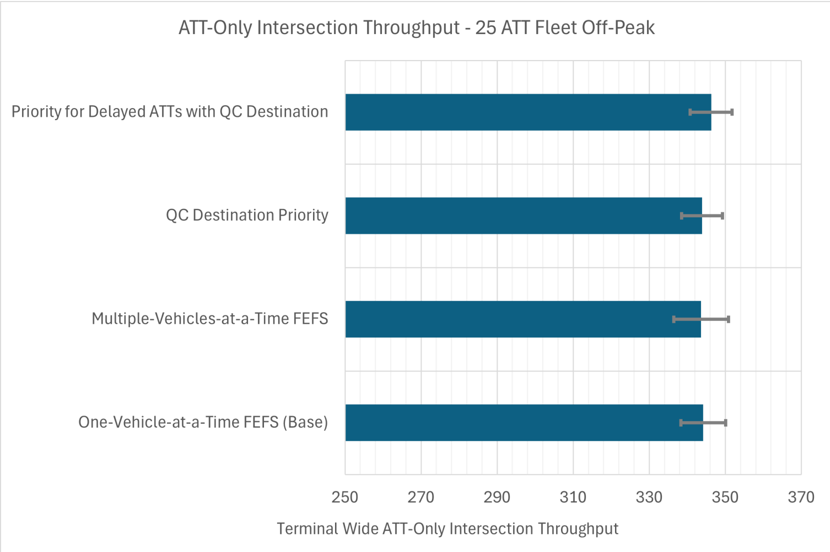

Figure B.16: Intersection throughput results for 20 (A)TT fleet configuration test in off-peak-load scenario

Intersection Throughput | 20 (A)TT Off- Peak-Load				
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio
One-FEFS	1	-	-	-
Multi-FEFS	0.266490987	1	-	-
QC-Prio	0.060431638	0.565019163	1	-
Delay-Prio	0.766008764	0.198818932	0.04968297	1

Figure B.17: P-value matrix of the Intersection throughput results for 20 (A)TT fleet configuration test in off-peak-load scenario

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B.3.5. 25 (A)TT Fleet Configuration | Off-Peak

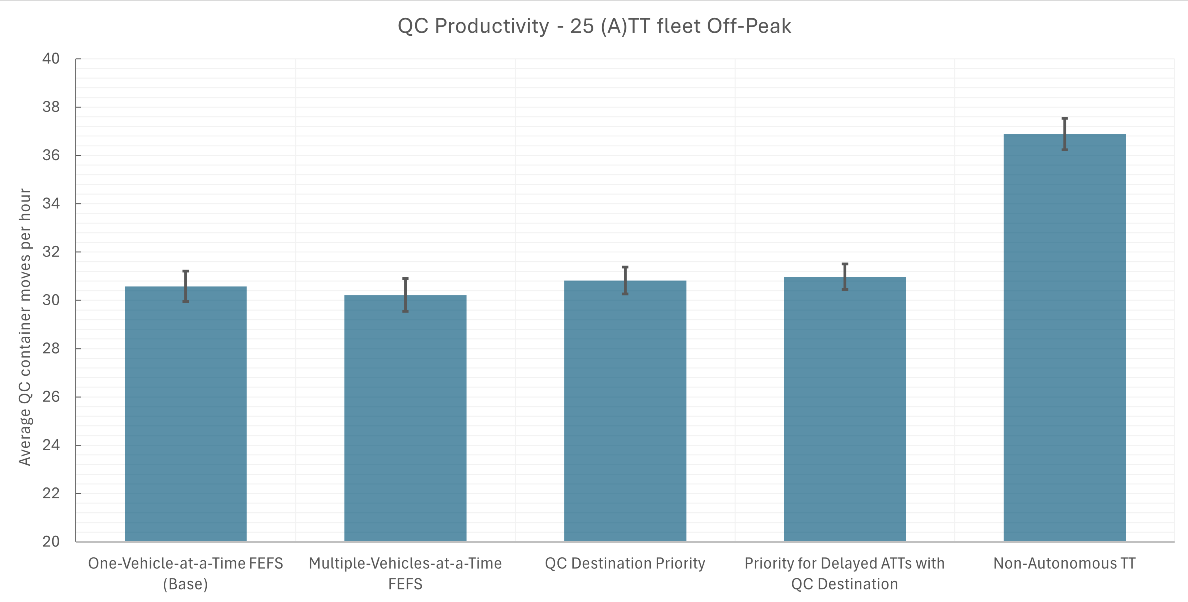

Figure B.18: QC productivity results for 25 (A)TT fleet configuration test in off-peak-load scenario

QC Productivity | 25 (A)TT Off- Peak-Load					
	One-FEFS	**Multi-FEFS**	**QC-Prio**	**Delay-Prio**	**Non-Autonomous TT**
One-FEFS	1	-	-	-	-
Multi-FEFS	0.414535961	1	-	-	-
QC-Prio	0.544740044	0.159181377	1	-	-
Delay-Prio	0.330018739	0.081361997	0.695449038	1	-
Non-Autonomous TT	1.30515E-22	1.54515E-23	7.27923E-22	2.71766E-21	1

Figure B.19: P-value matrix of the QC productivity results for 25 (A)TT fleet configuration test in off-peak-load scenario

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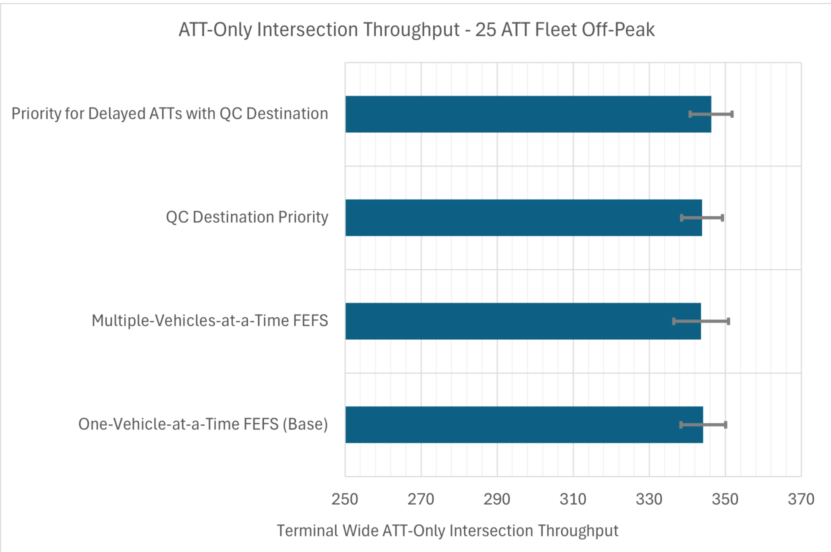

Figure B.20: Intersection throughput results for 25 (A)TT fleet configuration test in off-peak-load scenario

Intersection Throughput | 25 (A)TT Off- Peak-Load				
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio
One-FEFS	1	-	-	-
Multi-FEFS	0.904150043	1	-	-
QC-Prio	0.936138603	0.957804273	1	-
Delay-Prio	0.596719485	0.547139158	0.524388736	1

Figure B.21: P-value matrix of the Intersection throughput results for 25 (A)TT fleet configuration test in off-peak-load scenario

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B.3.6. 30 (A)TT Fleet Configuration | Off-Peak

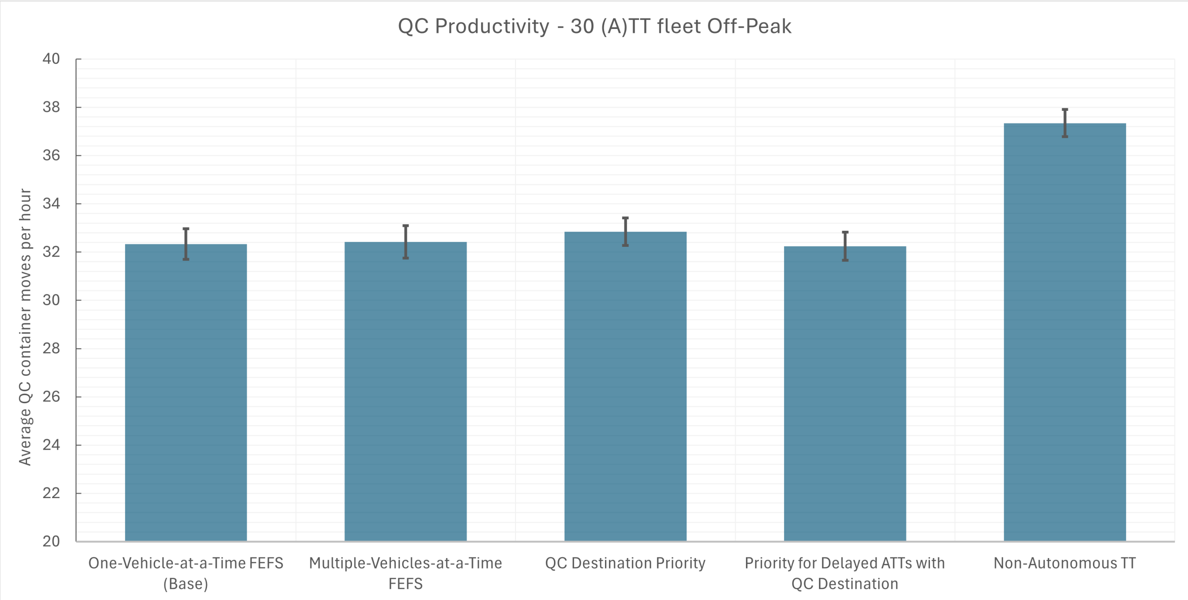

Figure B.22: QC productivity results for 30 (A)TT fleet configuration test in off-peak-load scenario

QC Productivity | 30 (A)TT Off- Peak-Load					
	One-FEFS	Multi-FEFS	QC-Prio	Delay-Prio	Non-Autonomous TT
One-FEFS	1	-	-	-	-
Multi-FEFS	0.849348564	1	-	-	-
QC-Prio	0.227933351	0.331092919	1	-	-
Delay-Prio	0.829177216	0.684118268	0.136755034	1	-
Non-Autonomous TT	1.51109E-19	1.34317E-18	8.03673E-18	9.57137E-21	1

Figure B.23: P-value matrix of the QC productivity results for 30 (A)TT fleet configuration test in off-peak-load scenario

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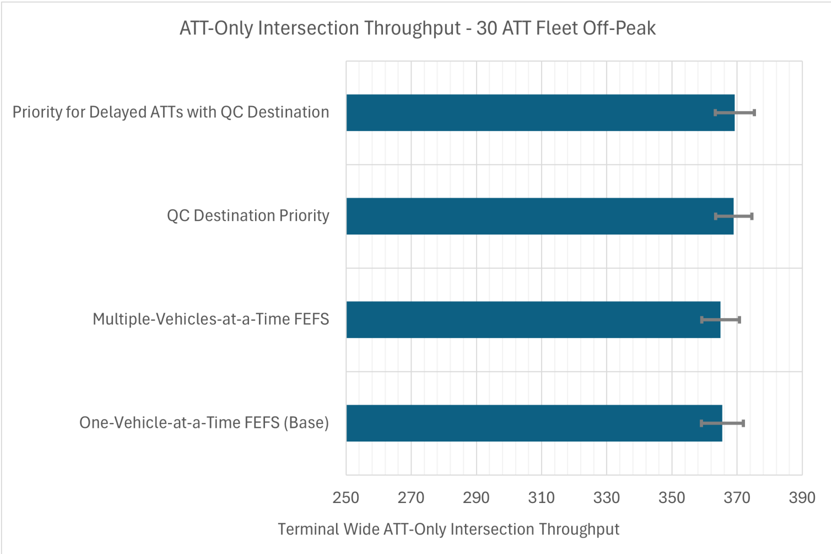

Figure B.24: Intersection throughput results for 30 (A)TT fleet configuration test in off-peak-load scenario

Intersection Throughput | 30 (A)TT Off- Peak-Load				
	One-FEFS	**Multi-FEFS**	**QC-Prio**	**Delay-Prio**
One-FEFS	1	-	-	-
Multi-FEFS	0.901538377	1	-	-
QC-Prio	0.41299005	0.320465032	1	-
Delay-Prio	0.385257238	0.299553329	0.933667599	1

Figure B.25: P-value matrix of the Intersection throughput results for 30 (A)TT fleet configuration test in off-peak-load scenario

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The QC move types tend to vary quite a bit between replications, as they would do between different days on a terminal as well. This should average out when enough replications are conducted, to roughly a 40% single load, 40% single discharge, 10% twin load and 10% twin discharge distribution for each strategy. The average distribution of the QC move types of all strategies and fleet configurations visualised in Figure B.26 and Figure B.27, approaches this desired distribution.

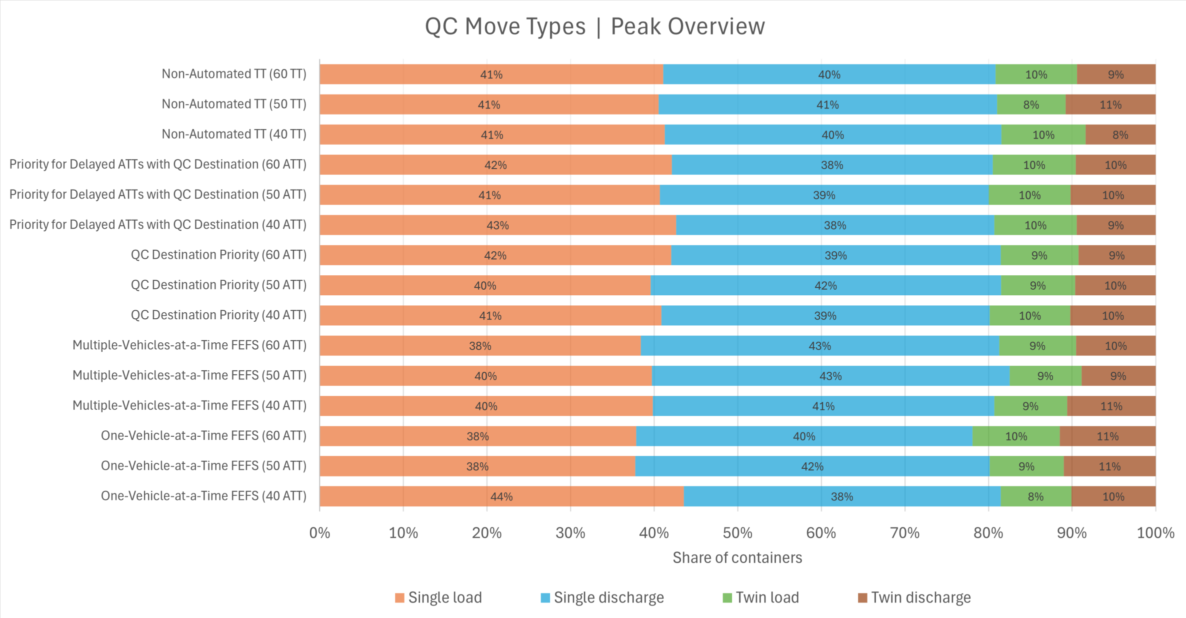

Figure B.26: Overview of the QC move types for the various (A)TT fleet configuration tests in peak-load scenario

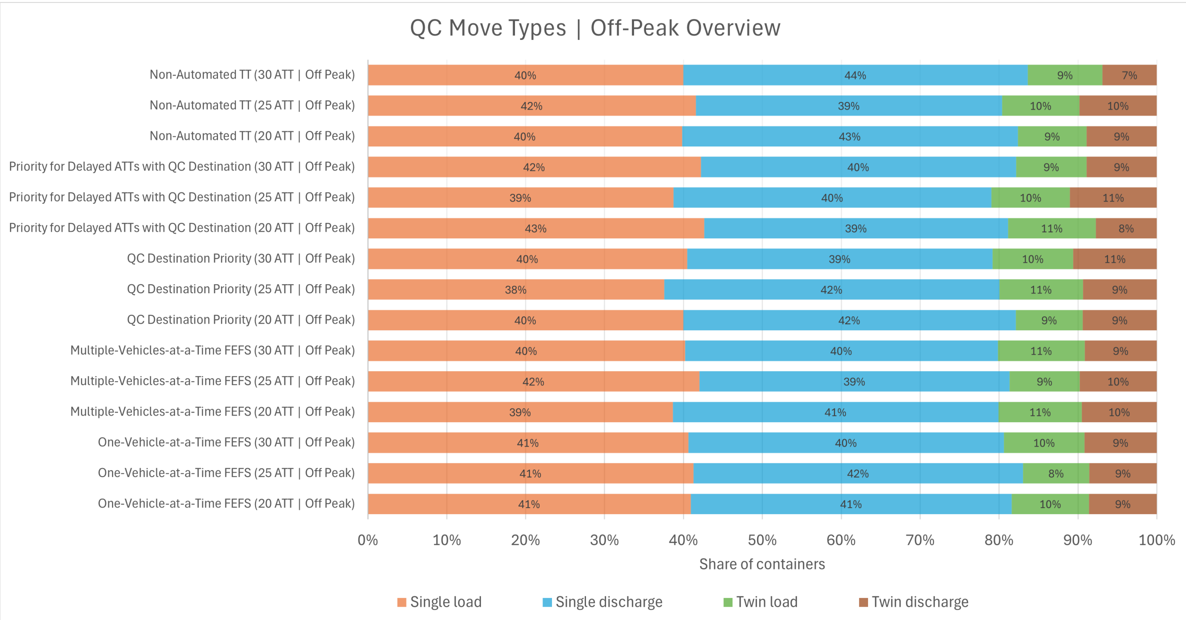

Figure B.27: Overview of the QC move types for the various (A)TT fleet configuration tests in off-peak-load scenario

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