Design of a traffic control system for autonomous vehicles in container terminals with mixed traffic

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List of Terms and Abbreviations

ACT - Automated Container Terminal
AGV - Automated Guided Vehicle
ATT - Autonomous Terminal Tractor
DES - Discrete-Event Simulation
ET - External Trucks
GMPH - Gross Moves Per Hour
KPI - Key Performance Indicator
RTG - Rubber Tyred Gantry
STS - Ship-To-Shore
TEU - Twenty-foot Equivalent Unit (size of one standard 20-foot container)
VTT - Vessel Turnaround Time

Brownfield terminal - Existing container terminals
Greenfield terminal - A designed container terminal that is not existing (yet)
Horizontal transport - Transport between a Ship-To-Shore system and a storage system.
Mixed traffic - Automated and manual traffic driving intermixed

Management Summary

Background

Due to the introduction of Autonomous Terminal Tractors (ATTs), it is now possible to mix autonomous and non-autonomous traffic in container terminals. ATTs are no longer centrally controlled but can make decisions themselves. This decentralization of control decreases error sensitivity. Typically, a central computer had to calculate the routes of all autonomous vehicles. When an error or conflict occurred by one of them, the computer had to calculate new routes for all the autonomous vehicles. The new and distributed way of control let ATTs communicate and solve problems between themselves.

The most important performance indicator of container terminals is the Vessel Turnaround Time (VTT). This is the time a vessel needs to berth at a container terminal before it can depart. By decreasing the VTT, the number of vessels a container terminal can handle increases. Consequently, container terminals can (un)load more vessels and vessels spend less time at terminals.

Problem definition

To successfully implement ATTs in container terminals, the requirements of the ATTs and the terminals they will be implemented in have to be investigated. This research focuses on suitable traffic control options in container terminals with *mixed traffic*. In addition, it aims to offer an insight into what equipment ATTs would need. Specifically, this research focuses on the bottlenecks of traffic environments: intersections.

Options

A traffic control mechanism of *mixed-traffic* environments consists of traffic rules that solve conflicts. A conflict occurs when multiple vehicles want to enter a road at the same time. These scenarios occur often at intersection areas. To gather traffic rules that can control *mixed traffic*, a literature study was carried out. A lot of research has been done in the last decade regarding traffic control of *mixed-traffic* areas. Mostly, research focuses on the smooth and safe throughput of all vehicles. In container terminals, another performance indicator plays a big role: the VTT. In addition to this Key Performance Indicator (KPI), the length of stay of the external trucks was recorded. Hence, both the performance of the container terminal at the quayside (VTT) and the landside (length of stay of external trucks) is measured.

Seven traffic rules for handling *mixed traffic* were found during the literature study:

- Priority from right
- Priority for ATTs
- Priority for external trucks
- Intersection manager with the objective to minimize the expected length of queues
- First Come First Serve
- Intersection manager with the objective to minimize acceleration/deceleration moments
- Priority based on urgency

Evaluation

Because experimenting in container terminals is not an option, the choice was made to evaluate the traffic control options in a simulation model. A representation of a container terminal was modelled in which 16 ATTs were present. The external trucks arrived with different arrival rates over the day.

The traffic control can deploy different traffic rules to make a distinction between vehicles based on multiple factors. However, to show the effect of all traffic rules they were implemented separately. This led to seven experiments that were carried out in 10 runs, in which every run represents a day.

Conclusions

After all experiments were carried out, it became clear that rule six: an intersection manager with the objective to minimize the expected length of queues scored best. The experiment in which rule six was implemented had the quickest VTT and the shortest length of stay of the external trucks.

The length of stay of the external trucks and the VTT seem to have a negative impact on each other. When the length of stay is short, the VTT tends to decrease. This can be explained by the fact that container terminals are less crowded when external trucks leave as fast as possible. When external trucks stay in the terminal for a long time, the terminal gets too crowded and waiting times of ATTs increase. Subsequently, the cranes that move the containers from the vessel on the ATTs are waiting, resulting in a longer VTT.

To successfully implement ATTs in container terminals, they need to be equipped with cameras or sensors with which they can look ahead. Decentralized control requires communication and local conflict handling. If rule six is to be implemented, ATTs should also be able to look behind them. The number of vehicles that are driving behind an ATT is equal to the length of the queue when the ATT is stopped. Whilst stopping the ATT would result in stopping every vehicle that is within a certain radius behind it.

Recommendations

Further research could combine traffic rules in the traffic control system. By combining traffic rules, the vehicle that should get priority can be chosen more precisely. Specifically, the order in which vehicles may cross the intersection, in such a way the KPIs are optimal, can be optimized.

In addition, the research could focus on dynamic traffic control. Traffic control options could be switched during the day to always use the optimal traffic control option per state. Experiments should show which traffic control options work best for certain states.

1. Introduction

Company

Distribute is a consultation company that provides insights based on simulation models. They design, create, and simulate distributed planning and control systems for the logistics and transport sector. By doing this, they are able to consult companies based on the outcomes of realistic simulation models. They base their consultation on the data of their simulations and are therefore able to make validated recommendations. Distribute works together with students of the University of Twente and they offered the chance to conduct a bachelor assignment at their company.

Project

Distribute has recently been asked to advise a company that has developed a new kind of Automated Guided Vehicle (AGV): An Autonomous Terminal Tractor (ATT). An AGV is a self-driven car and was introduced in 1993. In container terminals, they are used for the transport of containers. In most container terminals, either autonomous or manual vehicles drive between the stacks to deliver or pick up containers. The vehicles drive between the ship and the stacks to load or unload a vessel and external trucks enter and leave the container terminal from the other side to transfer the containers over land.

In container terminals with AGV systems, autonomous and non-autonomous traffic is strictly separated. The AGVs operate at the quayside and the external trucks at the landside. Container terminals that want to use AGV systems have to be designed specially. However, due to recent technological development, it is now possible to mix automated and manual traffic. The introduction of the ATT exemplifies this, because they are able to drive in *mixed traffic*. These ATTs could also be implemented in already built terminals that are not fit for AGV systems. However, before they can be implemented research has to be done on what the impact would be on the performance of container terminals.

The situation where autonomous and non-autonomous vehicles would both be driving in the container terminal could lead to conflicts. An example of this is an intersection, where multiple vehicles want to cross the intersection at the same time. To solve these kinds of conflicts, traffic control is needed. A traffic control system consists of traffic rules and prioritizes certain vehicles over others. How a traffic control system prioritizes depends on the traffic rules that are implemented. The goal of this research is to give insight in which equipment the ATTs would need to drive safely and efficiently in a container terminal with a certain traffic control system.

Academic relevance

Typically, AGVs are controlled by a central system. Such a system is sensitive to failures, while all AGVs will stop when the central computer is down. To decrease the dependency on a central computer, onboard vehicle control was developed. A system in which every vehicle controls itself but also communicate with each other is called a Multi-Agent Systems (MAS). MAS uses a distributed manner of problem-solving and this means that problems are solved by multiple agents (e.g. AGVs) by sharing information instead of a central control system. Balaji and Srinivasan (2010) describe it as: "*MAS can be defined as a network of individual agents that share knowledge and communicate with each other in order to solve a problem that is beyond the scope of a single agent*" (p. 2). This research will investigate options to implement self-controlled vehicles in container terminals to improve efficiency.

2. Theoretical Background

Nowadays, there is a growing pressure on supply chains and therefore also on container terminals. Container terminals can be seen as the link between the land- and seaside. Every container that is shipped over sea, eventually has to come ashore via a container terminal to reach its destination. A container terminal can also serve as storage if a container needs to be transferred from one vessel to another (Henesey, Davidsson, & Persson, 2008). The importance of minimizing the Vessel Turnaround Time (VTT), the time a ship must berth before it can depart, keeps increasing. The daily costs of berthing a ship with a capacity of 18.000 TEUs (the standard size of one 20-foot container) is estimated to be around $74.300,- (Kavas, 2016).

Furthermore, the ships are still getting bigger and therefore it is becoming even increasingly expensive to have delays. It has been calculated that when a Ship-To-Shore (STS) crane (*Figure 1*) moves four containers more per hour to/from the ship than it currently does, it will save $800.000 per STS-crane per year (Gangwani, 2015). The costs are not only high for the ports, but also for the shipping companies. Ship managers obviously prefer terminals with the highest efficiency and the lowest waiting time (Abijath & Kokila, 2017). In summary, the efficiency of a terminal does not only save money on the short term but is also a competitive advantage for the long term. Terminals become more attractive for ships if the VTT is as short as possible.

Figure 1: Two STS-cranes unloading a vessel

A container terminal consists of an STS system and a storage system. The STS-system facilitates the transportation of containers from the vessel to the land or the other way around. Once a container is unloaded from a ship, it has to be brought to the storage system. This is often a stack with a Rubber Tyred Gantry (RTG) crane (*Figure 2*), which loads the containers from the stack on the AGVs or the other way around. The transport from the STS system to the storage system is also known as *horizontal transport*. One of the main goals is to make sure that *horizontal transport* is organized as efficiently as possible (Valentina, 2014). To realise this goal, Automated Guided Vehicles (AGVs) were introduced in 1993. AGVs are autonomous driving vehicles that are used for the *horizontal transport* of materials (Vis, 2004).

Figure 2: RTG crane loading a container on a stack

Container terminals can be divided in *brownfield terminals* and *greenfield terminals*. *Greenfield terminals* are to be build and therefore provided with the newest technologies. *Brownfield terminals* are terminals that already exist. Automation of these terminals is done step by step, so the terminals can keep operating at the same level. Implementation of the newest technologies into container terminals that already exist is costly but can increase efficiency. Before such implementations are realized, analyses are conducted and terminal layout planning is done (Hendriks, 2014).

Islam and Olsen (2011) state that the capacity of a terminal strongly depends on the following factors: (i) the size of the storage yard, (ii) the performance and the number of cranes that are used and (iii) the availability of supportive transports. The unavailability of equipment is often one of the major causes of VTT delay (Abijath & Kokila, 2017). Therefore, big container terminals are making use of as much automated technologies as possible. The AGVs drive between the STS system and the storage system, making them much better connected and the process more reliable (Valentina, 2014).

Typically, AGVs were bound to a specific path: driving from a pick-up point to a delivery point following a predetermined path. More recent AGVs include technology that enables them to drive without a predetermined path. When a container has to be transported, an available AGV is assigned to pick up the container. Subsequently, a route to the destination is planned and as soon as the container is delivered and unloaded from the AGV, it becomes available again for a new assignment. Due to the absence of predetermined paths, the number of on-road decisions increases. A high level of control is needed to make sure the routes of the AGV system is efficient and to avoid deadlocks (Vis, 2004).

In 2003, Xu, Van Brussel, Nuttin, & Moreas describe a dynamic obstacle avoiding model. It concerns a system in which AGVs only use local information of the nearby environment. This has as a consequence that the AGV does not always drive an optimal route, but is able to react fast and avoid obstacles on the very last moment. Using such a reactive obstacle avoidance system saves a lot of computational effort. In addition, AGVs are able to avoid each other without intervention of a central planning system.

This decentralized coordination of AGVs is considered to become the standard in the future, while the computational complexity and the time that is needed for it is already often the performance bottleneck. However, the decentralized (or distributed) approach makes it possible to upscale easier while ATTs are able to handle dynamic avoidance themselves (Bahnes, Kechar, & Haffaf, 2016).

In *Figure 3* (Gerrits, Mes, & Schuur, 2018), a display is shown that represents a part of an Automated Container Terminal (ACT). On the right, the containers are delivered by external truck drivers and stacked in different rows by RTG cranes. When a vessel has to be loaded, containers are picked up by Autonomous Terminal Tractors (ATTs) from the stacks. They are then brought to the quay, where they are loaded onto the ship by Ship-To-Shore (STS) cranes. This process also happens the other way around. When containers are loaded from a ship and brought to a stack, it is called an import job and when they are loaded from a stack onto a ship it is called an export job (Gerrits et al., 2018).

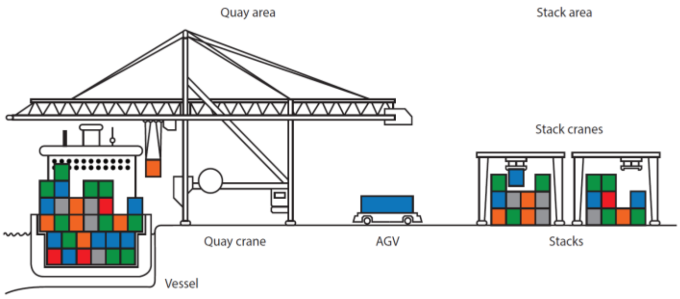


Figure 3: The standard layout of an ACT

3. Problem Context

In this chapter, the problem will be described and divided into different parts. In *Section 3.1,* the core problem will be identified and explained. Subsequently, the core problem will be divided into different parts to be able to solve it. In *Section 3.2*, research questions will be devised for every part. Furthermore, the research structure (*Section 3.3*) and the scope of the research (*Section 3.4*) will be discussed.

3.1 Problem identification

Two of the most used container terminal configurations are the parallel stack layout and the perpendicular layout. In *Figure 4*, the parallel layout is shown on the left and the perpendicular layout is shown on the right (Roy et al., 2014). A parallel container terminal layout is mainly applied in Asian terminals, whereas the perpendicular layout is often used in Europe. In a perpendicular layout, the transfer of containers from the quay to the landside is done automatically. The AGVs bring the containers to the beginning of the stack and the stack cranes move the containers to the other side, where external trucks can pick them up. This layout enables quick transporting of containers between the landside and the quay side. For terminals in which the majority of the containers is exported to land or imported from land, the perpendicular layout is used. For container terminals that mainly facilitate export jobs from one ship to another ship, it is easier to keep the containers closer to the quay. Therefore, the parallel layout is used in these kinds of terminals.

In a container terminal with a perpendicular layout, AGVs drive in the area between the stacks and the quay to transport containers. Another crane, that hangs on top of the stack, brings the containers to the other side of the stack, where the external trucks pick them up. The external trucks and the AGVs never encounter each other and there are no crossings. The AGVs and external trucks drive in loops. In container terminals with a parallel layout, AGV use is limited due to their inability to avoid conflicts. AGVs can drive pre-programmed routes and carry out tasks, but they cannot be used in dynamic environments. However, due to recent technological development it is now possible to mix automated and manual traffic. The introduction of the ATT exemplifies this, while they are able to drive in *mixed traffic*. This offers the chance to automate brownfield container terminals with a parallel stack layout.

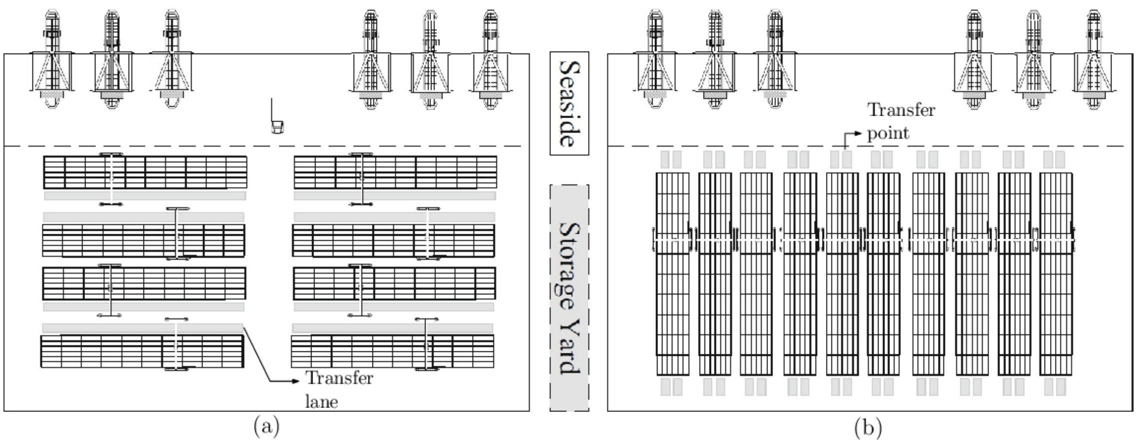


Figure 4: Most used container terminal configurations: a) parallel layout, b) perpendicular layout

A company that has recently developed a new Autonomous Terminal Tractor (ATT) approached Distribute and asked for insights in what kind of equipment the ATT would need. An ATT is an autonomous vehicle that is newly developed and can be used in container terminals to transport containers. The hardware of the new ATT is finished, but the software and the equipment are yet to be installed. To make the ATT as attractive as possible for potential buyers, it should be able to drive efficiently and smart. Therefore, it should be equipped with the right sensors, cameras and logic.

While the ATT will eventually be used in container terminals, it is important to look at the properties of this environment. The most important goal of a container terminal is to load or unload vessels as quickly as possible to be able to guarantee a short VTT. The task of ATTs in this process would be delivering the right containers on the right time. Mainly, three jobs can be distinguished in a container terminal and these are shown in *Table 1*.

Table 1: Different types of jobs

Type	**From**	**Temporary storage**	**To**
Import job	Ship	Import stack	Truck
Export job 1	Ship 1	Export stack	Ship 2
Export job 2	Truck	Export stack	Ship

When a fully loaded vessel has berthed, import jobs and export jobs of type 1 are carried out. With these jobs, it does not matter in which order the ATTs would arrive at the quay. They pick up a container and transport it to a specified place in a stack. When an empty vessel has berthed and needs to be loaded, the order in which the ATTs arrive at the quay matters. Vessels have a certain order in which the containers must be loaded, because the containers that have to be unloaded first have to be on top. The order in which containers, and thus the ATTs they are transported with, have to arrive at the quay affects the design of the traffic control system. The availability of the right containers at the quay is an important factor in the VTT. If an STS-crane is idle for a long time due to the unavailability of the right container, the VTT increases and that is getting costlier every day.

The ATTs will facilitate the *horizontal transport* in container terminals. Therefore, the ATTs will be responsible for the availability of the right container at the quay. The traffic control system determines which vehicles get prioritized and it can base this choice on different factors. The ATTs in a container terminal will be part of a MAS. As quoted earlier in the introduction, Balaji and Srinivasan (2010) describe a MAS as: "*a network of individual agents that share knowledge and communicate with each other in order to solve a problem that is beyond the scope of a single agent*" (p. 2). In this case, the ATTs are the individual agents that share knowledge and communicate with each other to solve certain conflicts.

The ATTs have the ability to handle conflicts with manual vehicles. For container terminals, this could mean that manual and automated vehicles could drive intermixed. To let autonomous and manual vehicles drive intermixed in a safely manner, clear rules should be established. There has not been done a lot of research into traffic control of container terminals with *mixed traffic*. This research is carried out in order to offer insights in what equipment ATTs would need in such an environment.

The causes of VTT delay can be divided into three subgroups: berthing delays, cargo handling delays and cargo unavailability delays. Berthing delays are mainly caused by the unavailability of berths, weather conditions and documentation or pilotage delays. The cargo availability delays are mainly caused by the unavailability of cargo or cargo that has no clearance. The last category, cargo handling delays, includes all delays that are caused by delayed processes in container terminals. One part of this category is the unavailability of *horizontal transport*. The *horizontal transport* is dependent on the ATTs. The ATTs operate as agents in a MAS and to be able to operate efficiently information has to be gathered, they have to communicate with each other, and a set of rules has to be determined to be able to handle conflicts. Thus, ATTs should be able to facilitate the *horizontal transport* in such a way that the VTT delay is minimized. This depends on the performance of the ATTs and the traffic control of the container terminal. Therefore, this research focuses on which traffic control in container terminals and equipment on ATTs would deliver a sufficient level of service regarding the *horizontal transport*.

The general problem cluster of brownfield container terminals with a parallel stack layout can be found in *Appendix A*.

The problem cluster ends with the fact that centrally controlled AGVs cannot drive in *mixed-traffic* environments. Therefore, the ATTs can offer a solution, but before they can be implemented, research has to be done into suitable traffic control and equipment that would be needed on them. This problem chain is presented in *Figure 5*.

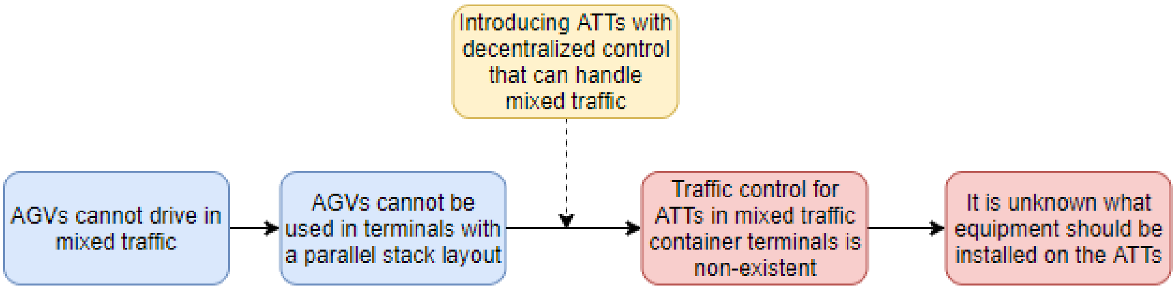


Figure 5: Problem chain of the introduction of ATTS

The problem identification has led to the following research objective:

- *'Increasing container terminal performance by finding an optimal traffic control for ATTs in mixed traffic.'*

To achieve the research objective, the core problem was devised and reads as follows:

- *'How to design an efficient traffic control system for ATTs in container terminals with mixed traffic?'*

3.2 Research questions

To achieve the research objective, several research questions have to be answered. Firstly, several traffic control options have to be found. They should concern the handling of a *mixed-traffic* environment and focus on the connection of autonomous and non-autonomous vehicles. Therefore, the first research question reads:

A. What are options to control traffic in a *mixed-traffic* environment?

Secondly, the effectiveness of the priority rules has to be tested. After the options have been analysed and an overview has been made of the scores of the various traffic control options, the best options will be chosen. An explanation will be given concerning their advantages and disadvantages. The second research question reads:

B. What are effective traffic control options in a *mixed-traffic* container terminal?

The results of question B give a clear overview on how the various traffic control options influence the performance indicators. The ATTs that are used in the container terminal need equipment and capabilities to make sure that they have the right information to drive safely and efficient in an environment where certain traffic control options are applied. Therefore, the last research question examines which equipment an ATT needs in accordance with the traffic control option that is chosen to be applied. This question will be answered for the best options that came out of research question B. The third research question reads:

C. How do the specified traffic control options affect the required capabilities of the ATTs?

After research question C has been answered, the gathered information will be used for an oversight in which the minimum needed performance of the equipment will be discussed. The speed of an ATT, the sensor distance and sensor direction are examples of aspects that depend on the traffic control and will be evaluated.

3.3 Research structure

For this research, the Managerial Problem-Solving Method (MPSM) is used. This method consists of seven different steps with which every action problem can be tackled in an efficient way. The steps are shown in *Figure 6*. During the applied execution of the MPSM one could encounter a point in time where he or she cannot continue due to a lack of knowledge. When this happens during this research, the research cycle will be used to solve the knowledge problem (Heerkens, 2015).

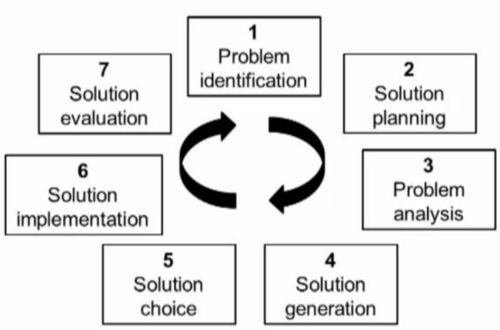


Figure 6: The Managerial Problem-Solving Method

The first three stages of the MPSM concern the identification and analysis of the problem. Based on this analysis, the research questions were devised. The fourth and fifth stage of the cycle concern the solution generation and choice. A literature study will be carried out to generate the solutions and the ones that are the most applicable will be chosen.

The 6th and 7th stage of the MPSM involve the implementation and evaluation of the chosen solutions. While the research focuses on a container terminal and experimenting in real-life is out of the question, the choice is made to gather data using a simulation model.

3.4 Scope

As explained in *Section 3.1*, this research focuses on the traffic control of container terminals with a parallel stack layout. With the introduction of the ATTs, the possibility raised to automate *brownfield terminals* with a parallel stack layout. Traffic control plays an important part in the implementation of ATTs in such environments. In addition to this, it is important that the ATTs are equipped to deal with *mixed traffic*. This research will offer an insight into the traffic control of ATTs in container terminals and the equipment they would need.

This research will focus on the bottlenecks of most traffic areas: intersections. In most container terminals, there is no room to overtake between the stacks. Therefore, intersections are the only points in container terminals where conflicts occur, and decisions must be made as to which vehicles get priority.

4. Traffic Control

In this chapter, the traffic control system will be introduced. In *Section 4.1*, a general introduction will be given, derived from literature. In *Section 4.2*, a literature study is carried out to find traffic rules to implement in the traffic control system.

4.1 Design of traffic control

The first part of this research focuses on the traffic control of container terminals. This has a big impact on the equipment that is needed on the ATTs. The traffic control is based on the combination of the information that is gathered by the ATTs and a clear set of rules. The traffic control is effective in intersection areas and determines which vehicles get to cross the intersection first.

Dresner and Stone (2008) introduced a reservation-based intersection control in which autonomous vehicles could reserve a piece of road for a specific time period. The new approach increased the performance of intersections significantly, while the precision of autonomous vehicles is more appreciated. While this was an improvement with respect to the traditional intersection control with static traffic lights and stop signs, the only rule that was tested was First Come First Serve (FCFS). So, although the new traffic control was a revelation, it did not prioritize incoming vehicles based on their urgency or importance, but solely on who arrived first. Therefore, Vasirani and Ossowski (2012) expanded the traffic control by implementing an auction method instead of the FCFS rule.

In a decentralized system, every ATT is focused to reach its own goal or destination. However, they have to be given tasks and when they are on collision course at least one of them must stop or reduce its speed. To be able to distinguish between ATTs and determine which ATT should get priority. Implementing an auction method is a popular way to determine which ATT should be prioritized. This method consists of two important objects. The first one is the auctioneer and the second one the bidder. The ATTs function as bidder and can make their bid based on some specified factors. The auctioneer compares all the bids it receives and determines which ATT should get priority (Fauadi, Li, & Murata, 2011).

The control of the ATTs is based on traffic control as described by Vasirani and Ossowski (2012). Each time a distinction in priority has to be made between ATTs, the auctioneer method will be used to decide which ATT gets priority. Examples of such situations are the assignment of tasks to the ATTs and when multiple ATTs arrive at the same crossing. ATTs that participate in the auction make a bid. The auction is based on multiple factors and the bid includes the score of the specific ATT on those factors. An example of this is whether an ATT is loaded or not. If the rule of the auctioneer is that loaded ATTs get priority over unloaded ATTs, the bid of the loaded ATT will score higher than the bid of an unloaded ATT. If two ATTs make a bid an both are loaded, the auctioneer will not be able to make a decision. Therefore, it is important that bids include multiple factors, so the auctioneer will always be able to prioritize one of the ATTs. When an ATT has won a bid, it gets the specific time- and space-bound reservation.

The factors that should be included depend on the traffic rules that apply. To decide which traffic rules will be implemented in this research, a literature study was carried out.

4.2 Traffic rules: a literature study

A literature study was conducted to identify traffic rules that are applicable to the control of ATTs. A full overview of the literature study can be found in *Appendix B*. The traffic rules that have been found are listed and explained below:

- *Traffic from right has priority*

  This rule is the simplest and does not take much into consideration. When two ATTs would approach an intersection, the ATT that comes from the right would get priority.

- *ATTs have priority*

  This rule is only applicable in *mixed-traffic* environments. In this scenario, external trucks would always have to give priority to autonomous vehicles. There are different ways in which this could be realized. Autonomous vehicles can communicate wirelessly. When they must stop, it can be communicated to them directly. However, this is not the case with non-autonomous vehicles and therefore some other hard- or software is needed. The articles state that implementing traffic lights is the option that is chosen the most. However, one article suggested the development of an app in which truck drivers can present themselves as an agent, just like ATTs. This would make traffic lights unnecessary and therefore save a lot of money. However, implementing traffic lights is a more robust and safe way of giving information.

- *External trucks have priority*

  This traffic rule is derived from the previous one. It states that external trucks should always get priority over ATTs. In some way, a distinction should be made between an external truck and an ATT. Once the external truck is signalized and the system sees it is approaching an intersection, the approaching ATTs are wirelessly told to stop.

- *The length of queues has to be minimized*

  This rule includes an intersection manager that tries to minimize the length of queues. For this rule, it is necessary to look further ahead. For example, when two vehicles are approaching from one direction and are on collision course with one vehicle that comes from another direction, the direction with the two vehicles will get priority. While the system then expects a queue of one instead of two.

- *First Come First Serve (FCFS)*

As stated earlier, this is the rule that was initially used by Dresner and Stone (2008). It simply gives priority to the vehicle that sends the first signal. Although it may not always be optimal, it is one of the most straightforward rules. Therefore, FCFS can still be used in making a bid. It makes sure that no ATT keeps standing still for a long time, while the FCFS part in his bid would become very large.

- *The total amount of time ATTs are decelerating/accelerating need to be minimized*

This rule is focused on the speed an ATT is driving. For example, when one ATT is standing still for an intersection due to a previous situation and another ATT comes from another direction and should give priority. However, the second ATT is driving at full speed and should therefore decelerate to let the other ATT pass. After that, it should accelerate again. When the second ATT is given priority, the deceleration and acceleration moments are avoided. This rule could result in waiting ATT that never get priority anymore (while everyone that is still driving get priority over them). Therefore, it would not work on its own entirely, but can be included in the bid a vehicle has to make.

- *Priority based on urgency*

Another rule that is often used to make a distinction between vehicles is the urgency factor. The type of urgency a vehicle gets can depend on its destination or what kind of vehicle it is. The type of vehicles is already included in the rules *'ATTs have priority'* and *'External trucks have priority'*. Besides the type of vehicle, the destination can be of influence on the urgency of a vehicle. For example, ATTs that are headed to the vessel could get a higher score than ATTs that are headed to a stack.

5. Simulation

To evaluate the proposed traffic control, the choice was made to implement it in a simulation model. In *Section 5.1*, a general explanation is given as to why simulation is a strong tool for this research. In *Section 5.2*, the conceptual model will be explained. In *Section 5.3,* the model will be explained in further detail. In *Section 5.4*, the traffic control system will be introduced and explained by an example. Lastly, the modelling of the traffic control system will be shown in *Section 5.5.*

5.1 General

Robinson (2014) describes simulation as: "Experimentation with a simplified imitation of an operations system as is progresses through time, for the purpose of better understanding and/or improving that system" (p. 1). The advantages of simulation over experimenting in a real system are cost, time, the level of control and experiments can be done even if the system does not exist in real-life. What's more, simulation is often used to visualize scenarios in order to create knowledge and understanding.

Container terminals would never cooperate with any experiments, because the risk would be too high to try out new configurations. However, simulation makes it possible to experiment in a realistic environment without the risk. Therefore, simulation is chosen as the analysis tool to carry out the experiments of this research.

Discrete-Event Simulation

Discrete-Event Simulation (DES) is a type of simulation that is mostly used for modelling queueing systems. Queueing systems involve entities that move from one activity to another. For example, a moving entity could be the ATT that moves the container through the container terminal and an activity could be the loading or unloading of the container. While the ATT must wait at the stack until the container is unloaded, the activities can be seen as a time delay for the moving entities. DES is often used to model manufacturing or transportation systems and this research will use DES to model a container terminal.

5.2 Conceptual model

In this section, the conceptual model will be explained. The main objectives will be described, along with the inputs, outputs, assumptions, and the level of abstraction of the model.

As explained in *Section 5.1,* the model will consist of discrete events. Examples of scenarios that will occur in a container terminal are loading/unloading a VTT at the quay, loading/unloading at a stack and crossing an intersection. The latter is of interest for this research. In the event an ATT enters a certain radius around an intersection, it will check if it is allowed to pass. Logic will be introduced which let the vehicles cross the intersection in the right order. The order will be determined by the traffic control system that will be introduced in *Section 5.4*.

The inputs of the model are shown in *Table 2*. All factors in the table are constant i.e. will be the same for every experiment, except for the traffic control. The layout of the container terminal will be the same for every experiment as well as the capacities of the ATTs and external trucks. The rate in which the external trucks arrive varies per hour. The arrival rate will be given per hour and will be the same for every experiment.

Table 2: Inputs of the model

Input	**Remark**
Number of stacks	A stack is a storage place where containers are put when they wait to be transported.
Number of STS cranes	The STS cranes load/unload the berthed vessel. The number of STS cranes is of great influence on the VTT but will not be varied during this research.
Maximum performance of STS cranes	The maximum performance of the STS cranes will be fixed. The performance of an STS crane is measured in GMPH.
Number of ATTs	The number of ATTs play a role in the crowdedness of the container terminal.
Maximum speed of ATTs	A higher maximum speed means that ATTs can move quicker between stack and quay.
ATT routing and task assignment	Logic will be implemented to determine the tasks of ATTs and their routes.
Traffic control in the container terminal	The traffic control will be implemented and experimented with.
Arrival intensity of external trucks	The arrival rate of ETs varies per hour

The most important output of the model is the VTT. The VTT is calculated from the moment a ship arrives until the moment it departs again. Earlier, VTT was expressed in days, but the container terminals have developed a lot over the past decades. Nowadays, the VTT is expressed in hours (Choo Chung, 1993). In addition to the VTT, the length of stay of the external trucks and the time an ATT spends in the system will be recorded. The latter will be divided into different categories. The performance indicators will now be explained further.

Vessel Turnaround Time (VTT)

The VTT is the key performance indicator. When a vessel berths at a container terminal, it pays the container terminal to load or unload a specified number of containers. The quicker that job is finished by the container terminal, the quicker a vessel can leave again. Obviously, the profit per time unit increases when jobs are carried out faster. Ships pay the same amount of money for a shorter stay and the container terminal can handle more ships per day.

Length of stay of the external trucks

This performance indicator will be added to record how much time external trucks spend in the container terminal. Whilst the main goal of container terminals is to minimize the VTT, the length of stay of external trucks may be considered as less important. However, it will be interesting to see what effects certain rules have on both.

Time division of ATTs

The ATTs drive between the stacks and the quay to transport containers from and to a berthed vessel. To get an insight into possible bottlenecks in the container terminal, the time spent by ATTs is recorded and divided into categories. The categories represent the different events of the model. The average speed and area of the ATTs will be recorded per category. At the end of a simulation run, which events took the most time and how much time ATTs spend on intersections.

Scope

To illustrate the impact of various traffic rules, this research focuses on a hypothetical container terminal with one berth, four STS cranes and 12 stacks. Every stack has one RTG crane to lift the containers from/on the ATTs/external trucks. The six stacks that are closest to the STS cranes are appointed for export jobs and the six other stacks are appointed for import jobs. An overview of this container terminal is shown in *Figure 7*. There are two different export jobs, namely from ship to ship and from truck to ship.

In *Figure 7* the routes of the external trucks (green) and the ATTs (red) are mapped. The green arrow represents the gate where the external trucks enter the ACT and the red arrow represents the gate where they leave the ACT. It can be seen that the routes of the ATTs and the external trucks cross at multiple points and that there are a lot of lanes in which they both drive. These points and lanes are critical and clear priority rules have to be set to guarantee safety and to optimize the availability of *horizontal transport*.

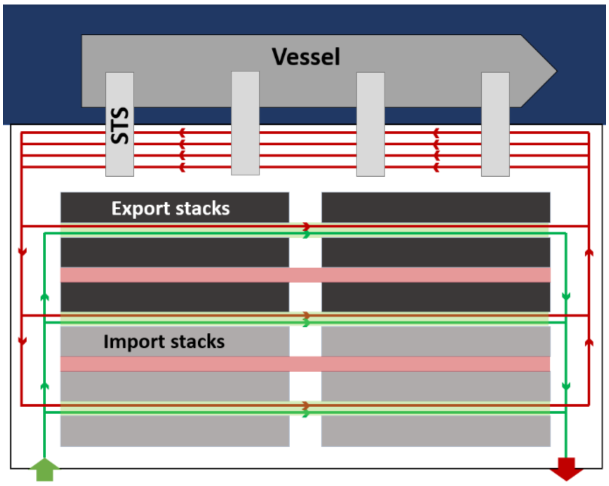


Figure 7: Routes of external trucks (green) and ATTs (red)

The RTG cranes can only (un)load containers at one side of a stack. In *Figure 7*, the routes of the vehicles are shown. They drive between the stacks in the green areas. The vehicles do not drive in the red areas between the stacks, while the RTG cranes are not able to (un)load at these sides of the stacks. Consequentially, the ATTs and external trucks drive in the same lanes and this results in crowded lanes and empty lanes.

Level of detail

The components of the model as mentioned in the 'Scope' paragraph will be modelled in such a way, that they are representative of the reality. However, some simplifications have to be made to improve the speed of the model. Only the important things are modelled, but a 3D model will be created to visualize the process. The components of the model will now be introduced, and the level of detail described.

STS cranes

The STS cranes will lift the containers from a berthed vessel on an ATT or the other way around. This process will have a cycle time and the maximum amount of moves one STS crane can make per hour will be 45. The average cycle time of one move will therefore be *(60 minutes * 60 seconds)/45 moves = 80 seconds/move.* A 3D crane will be imported to visualize this process. When an ATT is underneath an STS crane and its container is unloaded or loaded, the ATT gets assigned a destination in the stack area.

ATTs

The ATTs will exist of a truck and a chassis. The truck will receive a destination in the stack area when it is at the STS crane and will receive a destination in the quay area when he is at a stack. The container will be loaded on the chassis. When an ATT gets appointed a destination, the shortest route is determined. The ATT will be equipped with a sensor to look in front of him. When the sensor sees an object in front of him, the method that determines which get ATT should get priority will be called.

External trucks

The external trucks will enter the container terminal from outside. When they come to drop off containers they are loaded, else they are unloaded. They enter container terminal with a destination in the stack area. When they arrive, they drop off or pick up the container and leave the container terminal on the other side. External trucks also exist of a truck and a chassis. They never enter the quay area.

Stacks

The stacks function as storage space of the containers. The containers are stacked here. Every stack has one RTG crane that can lift the containers from an ATT onto the stack or the other way around. Containers can only be put on or lifted off the stack from one side. When an ATT has arrived at its destination in the stack area, the RTG crane will lift its container on the stack or lift a container from the stack on the ATT. When this process is rounded up, the ATT gets assigned a destination in the quay area. A destination in the quay area is always one of the four STS cranes.

Vessel

There will be one berth place in the model. This means that there can berth one vessel at a time. The vessel will have multiple bays and every STS crane will be able to empty multiple bays. The function of the vessel in the model is resembling with the stacks, containers can be stacked on it in different bays.

5.3 Model

The model that will be used for this research is previously built by Distribute. The model is developed with the program Plant Simulation. To make the model useful for this research, some changes were made. For example, the division of time spent by the ATTs was not recorded yet and the new traffic control was implemented. The logic that was added will be elaborated upon in *Section 5.5*.

Model

Several programs are available for the modelling of discrete events. The container terminal was modelled in Plant simulation. Plant Simulation is used to model operational processes in de manufacturing, health, and logistics sectors.

The model that will be used in Plant Simulation will now be introduced. In *Figure 8*, a top view of the model is shown. A full vessel is berthed in the upper side of the picture and four blue STS cranes are unloading it. The ATTs are driving underneath the STS cranes and in the stack area. The semicircle in front of them represent the sensor distance they are checking. In total, there are 12 stacks and three different lanes. In each lane, an ATT can unload or load at two sides.

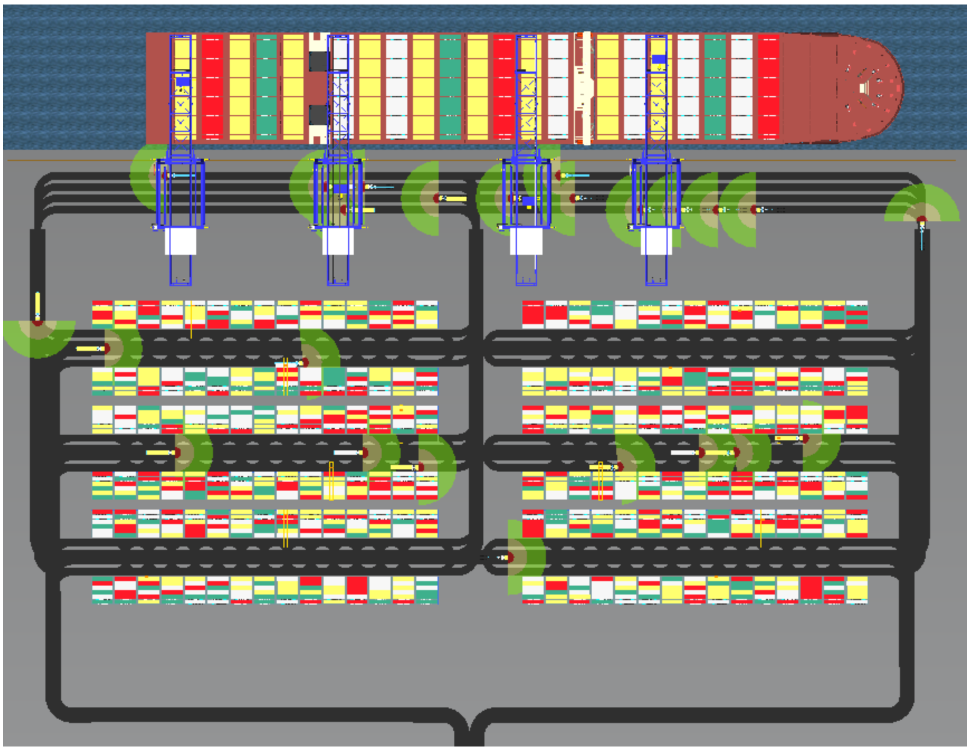


Figure 8: Top view of the container terminal model

In *Figure 9*, the model is shown in 3D. Every bay on the vessel can store 22 containers beside each other and 9 on top of each other. There are 21 filled bays on the vessel, which means that a full vessel carries *21*22*9 = 4158 containers*.

Figure 9: The modelled container terminal

Scenarios

The ATTs in the model check every 0.1 second where they are and if there are any objects within their sensor distance. When an object is within their sensor distance, they reduce speed. When the object is too close, the ATTs stop. When the ATT can safely drive, it checks where it is. In the event an ATT enters the stack, quay or intersection area, one of the three following scenarios is called: (i) an ATT is driving in the quay area, (ii) an ATT is driving in the stack area, (iii) an ATT is driving in an intersection area. In addition, the ATT also checks its sensor distance when it is driving in a stack, quay or intersection area, because it should always stop when an object is too close. As stated in *Section 5.2*, ATTs load or unload under STS cranes at the quay and get assigned a destination in the stack area. When ATTs arrive at their destination in the stack area, they load or unload under the stack cranes and get assigned a destination in the quay area. The first two scenarios will now be presented by flowcharts. They were already added by Distribute. The logic of the intersection and the traffic control was added for this research and will be elaborated upon in *Section 5.5.*

In *Figure 10*, the scenarios i and ii are presented by flowcharts. In both scenarios, the ATT checks if it has arrived. If so, the ATT is (un)loaded by an RTG crane (stack area) or an STS crane (quay area). Subsequently, a new destination is assigned to the ATT, where it should deliver or pick up a container. The ATT is assigned a destination in the stack area when it is at the quay and the other way around.

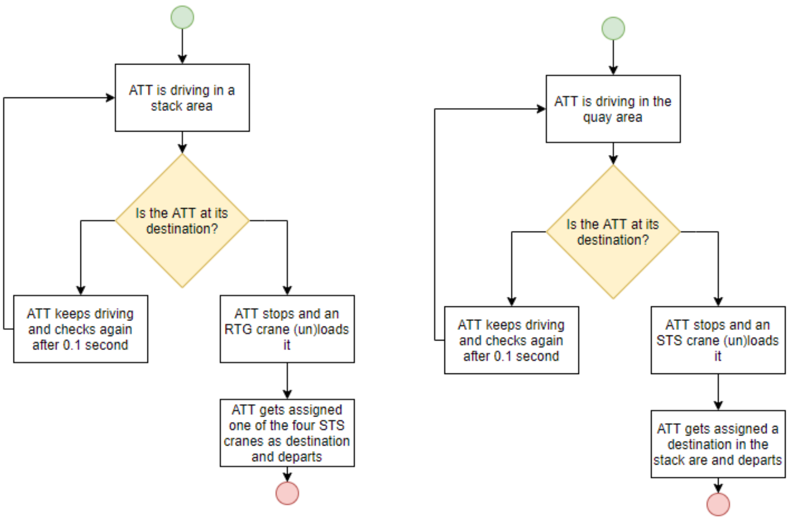


Figure 10: Flowchart of the scenario an ATT drives in the stack area (left) and in the quay area (right)

Output

VTT

For the VTT in this research, the assumption is made that the VTT is directly proportional with the average GMPH of the STS cranes. The number of STS cranes (4) and all attributes and properties that belong to them are fixed. A positive difference in GMPH will lead to a quicker VTT and a negative difference in GMPH will lead to a slower VTT. The only factor that will be changed is the traffic control, so all the differences that will be measured are caused by the traffic control. The factors that will be varied and the ones that will not be varied are further explained in *Section 5.4*.

Length of Stay of External Trucks

To keep track of the time external trucks spend in the container terminal, the length of stay is recorded. The length of stay is recorded from the moment they enter the system until they leave the system.

Division of time spent by ATTs

To evaluate the different scenarios of the various solutions and the current situation, a method was written to map the activities of the ATT. This method distinguishes between different speed modes and locations. The different speed modes are normal, reduced and standing still, in which reduced contains all speeds that are neither normal nor 0.

Every time an ATT changes it speed, a method is called that writes the starting time and the location of the ATT in a table. The next time the ATT changes its speed, the method closes the time period and writes the time period and the location at which it started in a definite table. After this, the ending time is used again as starting time of the next period. A flowchart of this method can be found in *Appendix C* and the code in *Appendix D*.

5.4 Traffic control

The inputs that were introduced in the conceptual model will now be further explained. The inputs will be given a value. Most of the inputs will not be variable. The values of the inputs are shown in *Table 3*.

Table 3: Values of the inputs

Input	Value
Number of stacks	12
Number of STS cranes	4
Maximum performance of STS cranes	45 GMPH
Number of ATTs	16
Maximum speed of ATTs	20 km/h
ATT routing and task assignment	When an ATT is at an STS-crane, a destination in the stack area will be assigned. If an ATT is at a stack, a destination in the quay area will be assigned. The shortest route will be chosen.

The arrival rate of the external trucks was provided by Distribute. It is based on the arrival rate of external trucks at container terminals on a normal weekday, i.e. Monday until Friday. The arrival rates are given per hour from 08:00 till 20:00. The arrival rates are shown in *Table 4*.

Table 4: Arrival rate of external trucks per hour

Hour	*8:00*	*9:00*	*10:00*	*11:00*	*12:00*	*13:00*	*14:00*	*15:00*	*16:00*
Arrival rate	67	45	45	45	54	63	72	76	89
Hour	*17:00*	*18:00*	*19:00*	*20:00*					
Arrival rate	112	112	89	67					

The input that will be experimented with is the traffic control. The traffic control is based on an auction method. The traffic rules that were found during the literature study in *Section 4.2,* will be implemented in the traffic control. Which rules are implemented and how big their factor is, depends on the experiment. In *Table 5* an overview is given of all the traffic rules that were found during the literature study and in what way their score is determined.

Table 5: Traffic rules and determination of scores

#	Traffic rule	Determination of score	Type
1	*ATT have priority over external trucks*	If this rule implemented ATTs get a 1 and external trucks a 0.	Boolean
2	*External trucks have priority over ATTs*	If this rule implemented external trucks get a 1 and ATTs a 0.	Boolean
3	*Minimization of expected length of queues*	Number of vehicles that come from the same direction and are within a certain radius of the intersection.	Integer
4	*First Come First Serve*	The order in which the bids come in is listed. The vehicle that send its bid as first scores 1, the other 0.	Boolean
5	*Minimization of acceleration/deceleration moments*	If a vehicle is standing still it gets a 0, if its driving full speed a 2 and if the speed is in between 0 km/h and full speed it gets a 1.	Integer
6	*Urgency (destination)*	If an ATT is headed towards the quay (destination STS crane 1, 2, 3 or 4. The STS cranes are listed and ranked on their length of queues. The shortest queue gets the highest priority, which is score 3. The others score 2, 1 and 0. External trucks do not have priority destinations.	Integer

While a vehicle in the model is either an ATT or an external truck, the first two rules cannot be used at the same time. Furthermore, the importance of the rules is represented by a factor. The total of factors will be 1.0. Lastly, the rule that gives vehicles from the right priority is not included in the bid. However, it will be used as a tiebreaker when vehicles have the same score.

To illustrate the way the auction method will work, an example will be given. For this example, all traffic rules are equally important, and ATTs have priority over external trucks. In *Table 6* the traffic rules are shown with their factor.

Table 6: Example of a bid based on a combination of traffic rules

#	Traffic rule	Factor
1	ATT *have priority over external trucks*	0.2
2	*External trucks have priority over* ATTs	0
3	*Minimization of expected length of queues*	0.2
4	*First Come First Serve*	0.2
5	*Minimization of acceleration/deceleration moments*	0.2
6	*Urgency (destination)*	0.2

The traffic control option is applied to the scenario that is shown in *Figure 11*. Vehicle 1 and 3 are ATTs and vehicle 2 is an external truck. Vehicle 2 and 3 both want to cross the intersection, but one of them must stop. Vehicle is not an ATT, so does not score points on the first rule. However, in the lane of the external truck is another vehicle. Therefore, the expected length of queues is 2 vehicles. For car 3 this is only 1. The external truck is closest to the intersection; therefore, it gets score 1 for the FCFS rule. After the truck comes vehicle 3 and vehicle 1 is the last. In this scenario, both vehicles are driving at a reduced speed, so they both score 1 point. Lastly, vehicle 3 is headed to the STS crane with the second shortest queue, so gets score 2. The external truck does not have an urgency destination. In *Table 7*, the calculation of the scores is shown.

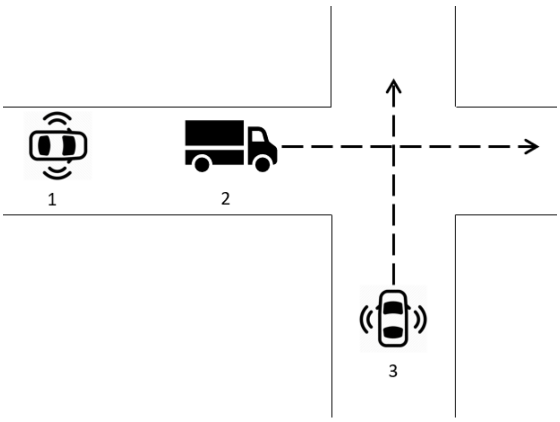


Figure 11: Example of a scenario

Table 7: Calculation of scores of example scenario

#	Traffic rule	Factor	Score vehicle 2	Score vehicle 3
1	ATT *have priority over external trucks*	0.2	0.2*0	0.2*1
2	*External trucks have priority over* ATTs	0	0*1	0*0
3	*Minimization of expected length of queues*	0.2	0.2*2	0.2*1
4	*First Come First Serve*	0.2	0.2*1	0.2*0
5	*Minimization of acceleration/deceleration moments*	0.2	0.2*1	0.2*1
6	*Urgency (destination)*	0.2	0.2*0	0.2*2
	Total score:		**0.8**	**1.0**

The total scores have been calculated and vehicle 3 scored 0.2 higher than vehicle 2. This means that vehicle 3 may enter the intersection first.

5.5 Modelling

In this section, it is shown how the traffic rules were devised and how they work. The event that triggers vehicles to. Before running an experiment, the factors of the auction method have to be given as input. The moment a vehicle is within a certain radius of an intersection, is the event that triggers the vehicle to pass through these steps. In *Figure 12*, a flowchart is shown of the steps a vehicle follows when the event of approaching an intersection occurs. A vehicle is not allowed to cross the intersection when (i) the intersection is not free (e.g. another vehicle is still crossing the intersection) or (ii) the intersection is free, but another vehicle has a higher score. When one of these scenarios occur, the vehicle is stopped. The vehicle starts driving again when the intersection is free and there are no other vehicles with a higher score that want to pass.

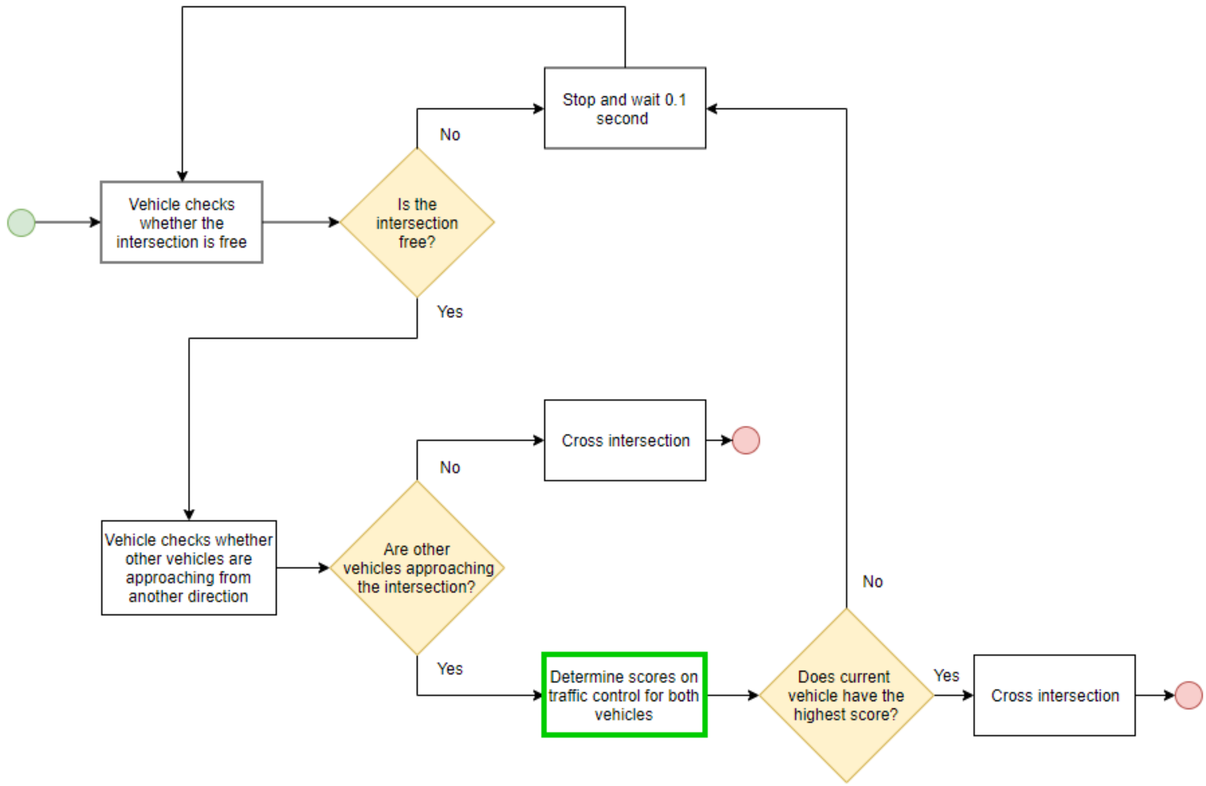


Figure 12: Flowchart of traffic control at intersections

One block in the flowchart has a green border. The determination of the traffic control score consist of multiple steps. In every step, the score of one traffic rule will be determined for the vehicles that want to cross the intersection. In the following paragraphs, the calculation of all traffic rules will be explained. After all scores are calculated, they are multiplied by their factor (which is given as input). The total of all multiplied scores is the overall score of a vehicle.

Rule 1 & 2: Priority is given to ATTs and ETs respectively

The first two rules were modelled in one statement. The code looks at the class of a vehicle. If it is an ATT, it scores a 1 on the first rule and a 0 on the second rule. For external trucks it is the other way around. In *Figure 13*, a flowchart is shown that shows the logic of the rule that was implemented.

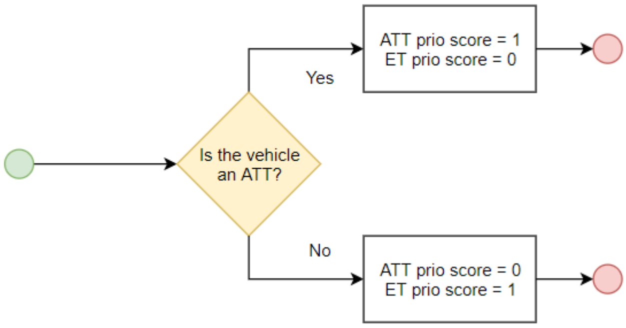


Figure 13: Flowchart of rule 1 & 2

Rule 3: Minimization of length of queues

This score was determined by looking to the number of vehicles on the same road as the truck that called the method and the number of trucks on the tracks before. Only the piece of tracks that are directly linked to the track the vehicle is on are included in the calculation. For example, if there are three tracks connected to the track on which the truck is located, the total number of vehicles that are on all four tracks determine the score. In *Figure 14*, a flowchart of this rule is shown. At first, the number of connected roads is determined. Subsequently, the expected queue is calculated by adding the vehicles on all connected roads and the road the vehicle is currently on.

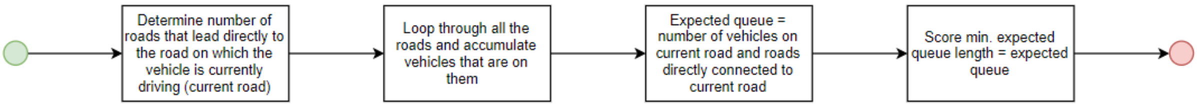


Figure 14: Code for rule 3

Rule 4: First Come First Serve

Due to the decentralized control, every ATT checks every tenth of a second if something is in front of him. If an ATT approaches an intersection and sees another ATT, the assumption is made that the first ATT is closer to the intersection. That ATT receives score 1 and gets priority over the other ATT. The default score of this rule is 0 and after an ATT has passed an intersection, it is put back to 0.

Rule 5: Minimization of acceleration/deceleration moments

The score of this rule was determined by looking at the speed a vehicle is driving when it approaches an intersection. An approaching vehicle can obtain three different scores:

- 2 for vehicles driving full speed
- 0 for vehicles standing still
- 1 for vehicles that are neither driving full speed nor standing still

In *Figure 15*, a flowchart is shown that represents the logic of rule 5.

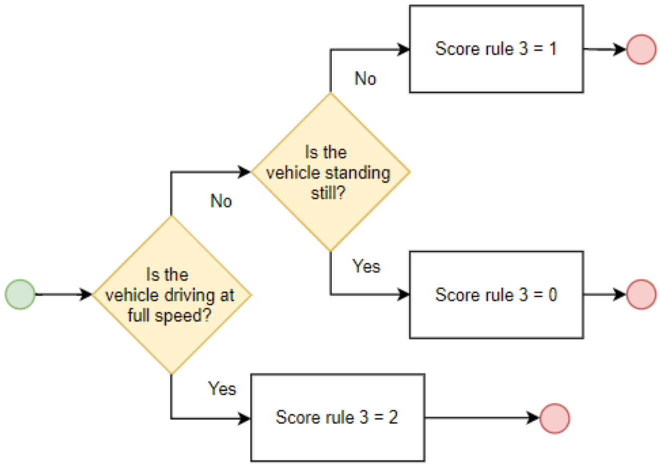


Figure 15: Code for rule 5

Rule 6: Priority based on urgency

This rule consists of two parts. Firstly, the STS cranes are ranked on the length of their queue. The STS crane with the longest row ranks fourth and the STS crane with the shortest row ranks 1. The code in *Figure 16* shows the ranking of the STS cranes. At first, the number of vehicles on the tracks underneath the cranes are looked up, then they are ranked from the longest queue to the shortest queue.

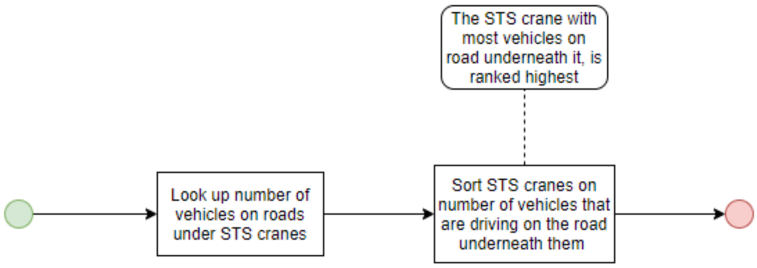


Figure 16: Rank STS cranes on the longest queue

After this, the method search for each vehicle what its destination is. When it is one of the cranes, it looks at the row that crane is ranked in. The score the vehicle receives is the *row of the crane – 1*. The crane with the longest queue will be ranked first. Therefore, it gets score *1 – 1 = 0* (lowest priority). The STS crane with the shortest queue, will be ranked fourth and therefore receives the score *4 – 1 = 3* (highest priority). If a vehicle has another destination than one of the STS cranes, it gets score 0. In *Figure 17*, a flowchart of the rule is presented.

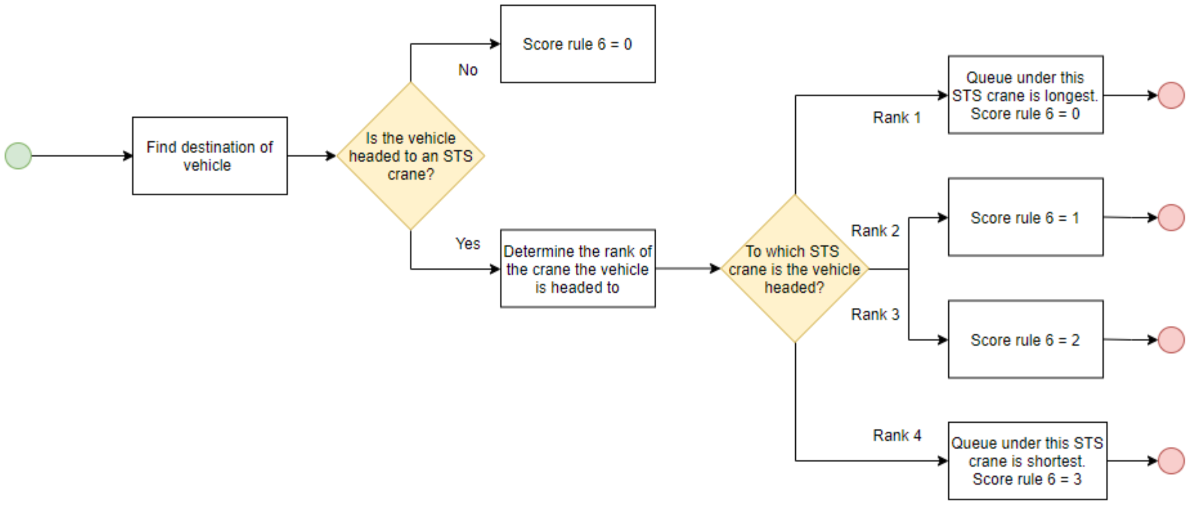


Figure 17: Code for rule 6

Eventually, all scores are cumulated and an overall score is determined the vehicles that want to enter the intersection.

The complete code can be found in *Appendix E*.

6. Experimental Design

In this chapter, the experimental design will be discussed. In *Section 6.1*, the experiments that will be carried out are discussed. In *Section 6.2*, the warm-up period is calculated. Finally, the number of runs that should be carried for each experiment will be discussed in *Section 6.3*.

6.1 Experiments

The experiments concern the factors that are given to the traffic rules. In the example that was given in *Section 5.4*, all rules were of equal importance in the auction. However, by making the factors bigger or smaller, some rules can become more important than others. Traffic rules can be excluded by setting their factor equal to zero.

In the first experiments, only one traffic rule will be active. This choice was made to obtain a clear insight into what effect these different rules have on the performance of the model. To illustrate the effect of the auction method, one experiment was added in which two rules are combined. After the first experiments have run, the two best performing rules will be combined. They will both have factor 0.5.

Whenever a traffic rule cannot make a distinction between vehicles, the vehicle from right will get priority. The experiments are shown in

Table 8*,* the numbers correspond with the following rules:

1. *ATT have priority over external trucks*
2. *External trucks have priority over ATTs*
3. *Minimization of expected length of queues*
4. *First Come First Serve*
5. *Minimization of acceleration/deceleration moments*
6. *Urgency (destination)*
7. *Combination of two best rules*

Table 8: Factors of traffic rules per experiment

Traffic rules → Experiments ↓	**Rule 1**	**Rule 2**	**Rule 3**	**Rule 4**	**Rule 5**	**Rule 6**
1	1	0	0	0	0	0
2	0	1	0	0	0	0
3	0	0	1	0	0	0
4	0	0	0	1	0	0
5	0	0	0	0	1	0
6	0	0	0	0	0	1
7	The two best rules of the previous experiments will be combined. Both rules will have factor 0.5.					

6.2 Warm-up period

The warm-up period was determined based on Welch's procedure (Law, 2015). Firstly, ten independent replications were made of the basic scenario. The basic scenario contains no additional priority rule besides the priority from right, there were 16 ATTs in the system and their normal speed was 20 km/h. The KPI that was measured was the average GMPH of the four STS cranes. The GMPH was measured every minute and the duration of a run was 8 hours. Therefore, there are 8 (hours) * 60 (minutes/hour) = 480 data points per run. The plot of the attained data points was already a smooth line. A moving average was calculated (w=1), but this made little difference.

In *Figure 18*, the plot of the averages is shown. The slope of the line starts to decline from 120 minutes. Therefore, the warm-up period is determined to be 120 minutes, this border is represented by the black line in the graph.

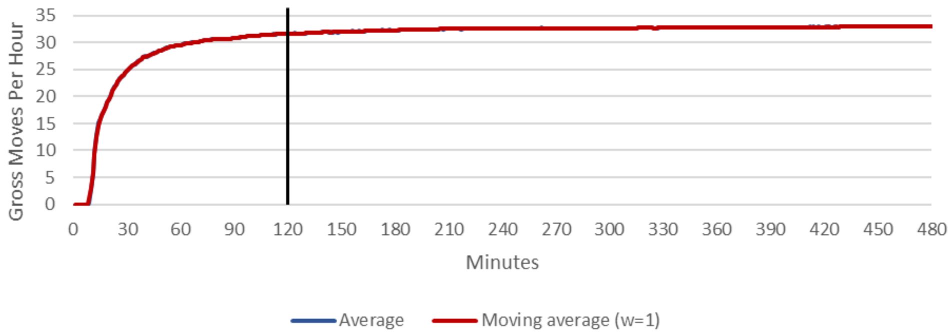


Figure 18: Plot of averages to determine warm-up length

6.3 Run length

To determine the number of required runs, the scenario without traffic control (base model) was simulated in 10 runs. The KPIs are measured every hour and there are 14 hours per run. During the first two hours, no statistics were recorded while this is the warmup period. For every measurement, 10 runs with different random numbers are generated. After every run half of the confidence interval was calculated and divided by the mean. In *Table 9*, the relative error after 10 runs is given for every hour statistics are recorded. The biggest error after 10 runs is 1.38%. This means that the confidence interval deviates at most 1.38% from the mean.

Table 9: Relative error per hour after 10 runs

Hour	**Relative error after 10 runs**	**Relative error after 10 runs (%)**
8:00 - 9:00	0,00345442	0,35
9:00 - 10:00	0,009202896	0,92
10:00 - 11:00	0,00360071	0,36
11:00 - 12:00	0,006605547	0,66
12:00 - 13:00	0,006833661	0,68
13:00 - 14:00	0,007651017	0,77
14:00 - 15:00	0,007813353	0,78
15:00 - 16:00	0,007435482	0,74
16:00 - 17:00	0,013808254	1,38
17:00 - 18:00	0,006899028	0,69
18:00 - 19:00	0,00403913	0,40
19:00 - 20:00	0,007818708	0,78

Most relative errors were lower than 0.025 after three runs. Because this number of replications is still relatively low, the choice was made to simulate all experiments in ten runs. It can be said with 95% certainty, that the obtained values after ten runs will not deviate more from the mean than the percentages that are shown in *Table 9*. For example, the average GMPH of ten runs that is measured between 16:00 and 17:00 will not deviate further from the mean than 1,38%.

7. Results

In this chapter, the results of the experiments will be presented. In *Section 7.1*, information is given that is needed to properly interpret the results. In *Section 7.2*, the results of all experiments are presented.

7.1 General

Seven experiments were simulated in ten runs of fourteen hours. During the first two hours, no statistics were recorded due to the warmup time. Therefore, every run consists of 12 hours and thus 12 data points. The first experiment considered the standard scenario with the traffic rule priority from right. If no decision could be made in experiment 2 to 7 because vehicles had the same score, the vehicle from right always got priority.

For all experiments, both the GMPH and the length of stay of the external trucks are given. To be able to interpret the results in the right way, the arrival rate of the external trucks should also be considered. The arrival rate of the external trucks was introduced in *Section 5.4,* and can also be seen in *Table 10*. Every day starts with a small peak, which then decreases. From 12:00 the arrival rate starts to increase, and the arrival rate is at its peak between 17:00 and 18:00. After that, it decreases again to the same level the day started with.

Table 10: Arrival rate of external trucks per hour

Hour	*8:00*	*9:00*	*10:00*	*11:00*	*12:00*	*13:00*	*14:00*	*15:00*	*16:00*
Arrival rate	67	45	45	45	54	63	72	76	89

Hour	*17:00*	*18:00*	*19:00*	*20:00*
Arrival rate	112	112	89	67

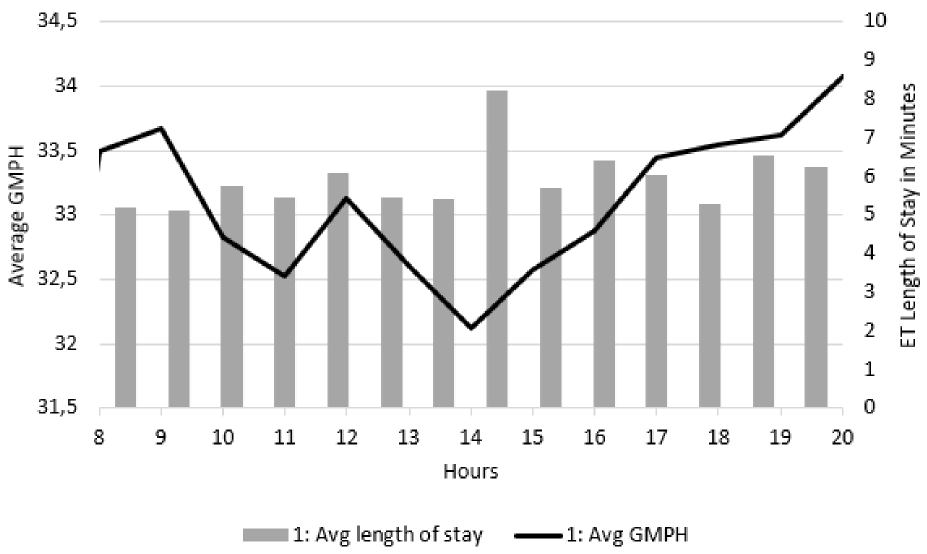
The first output that is looked at was the time division of the ATTs. This research only focused on the period in which vehicles try to cross an intersection. This period starts in the event a vehicle approaches an intersection and stops when it has crossed. In the twelve hours that the simulation was run, every ATT spent 4.5 minutes on average crossing intersections. Therefore, the average percentage of time an ATT spends at intersections is approximately 1%. Any positive changes of the KPIs that is seen in the next paragraphs is achieved by optimizing an event that thus takes relatively little time.

7.2 Experiments

In this section, the results of all experiments will be considered. Firstly, the standard scenario (priority from right) will be discussed. Subsequently, all other experiments will be considered and compared with the standard scenario. Experiment 2 (ATT priority) and experiment 5 (FCFS) made no difference. For the results of experiment 2 and 5, see the result and figure of experiment 1. Possible reasons why the experiments made no difference are discussed in *Chapter 8*.

Experiment 1: Priority from right

In experiment 1, vehicles that come from the right have priority. The results of the simulation of experiment 1 are shown in a graph that is presented in *Figure 19*. The length of stay of the external trucks is represented by the grey columns and the GMPH by a black line. Statistics of the KPIs are shown in the table beside the graph. The GMPH is around the 33.5 after the first hour. After that, the GMPH starts to decline and the average length of stay of the external trucks stays approximately the same. After six hours, the GMPH starts to decrease and the length of stay increase. On that moment, the external trucks spend a lot of time in the container terminal and the GMPH is at its lowest point. After this moment, the arrival rate of the external truck increases, but also the performance of the system: the GMPH increases and the length of stay decreases. During the busiest hours (11 and 12: arrival rate of 112 ETs per hour), the GMPH increases slightly and after the busiest hours the GMPH continues to increase to 34.



Statistics

GMPH	
Average	33,12
Variance	0,33
Min	32,13
Max	34,01

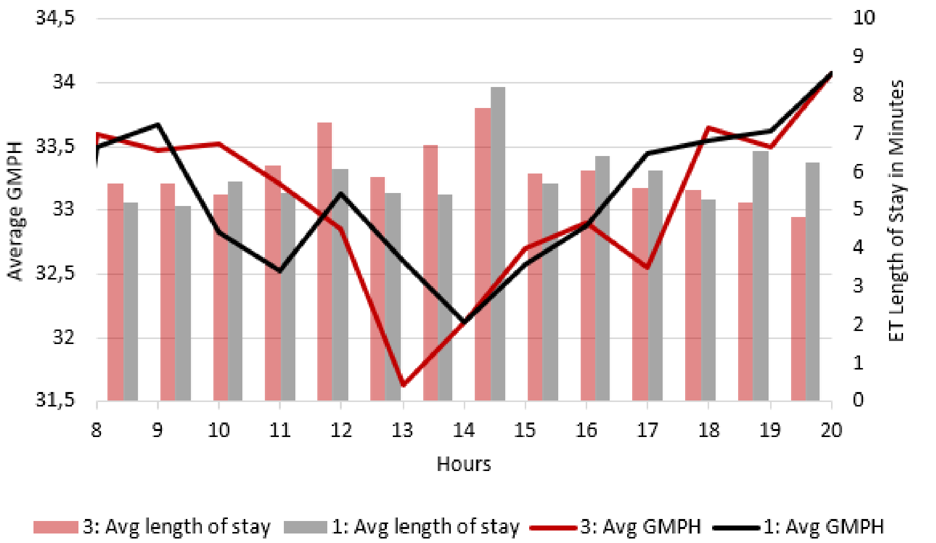
ET Length of Stay (min)	
Average	5,99
Variance	0,65
Min	5,13
Max	8,21

Figure 19: Results experiment 1

Experiment 3: ET priority

In *Figure 20* the KPIs of experiment 1 (GMPH: black line, Length of Stay: grey columns) and 3 (GMPH: red line, Length of Stay: red columns) are shown. In experiment 3, the external trucks get priority over the ATTs. At the beginning, the length of stay of the external trucks is slightly higher than experiment 1. After ten hours, when the external truck arrival rate is approaching its peak, the length of stay decreases faster than in experiment 1. At the end, the difference is almost one minute.

The GMPH performs better at the beginning than in experiment 1. However, when the external truck arrival rate starts to increase, the GMPH decreases dramatically. The minimum GMPH is 31,60 and occurs at 13:00 hour. After this low point, it starts to increase again but it does not seem to outperform experiment 1.



Statistics

GMPH	
Average	33,06
Variance	0,47
Min	31,60
Max	34,00

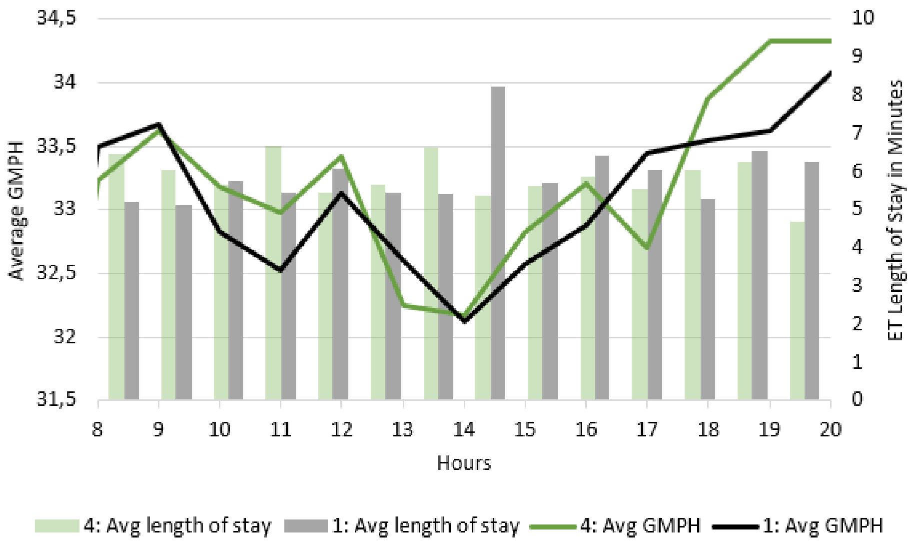
ET Length of Stay (min)	
Average	6,00
Variance	0,66
Min	4,81
Max	7,68

Figure 20: A comparison of experiment 1 & 3

Experiment 4: Minimization of the expected length of queues

In experiment 4, the expected length of queue is minimized. The KPIs of experiment 1 (GMPH: black line, Length of Stay: grey columns) and 4 (GMPH: green line, Length of Stay: green columns) are shown in *Figure 21.* The side from which the most vehicles arrive gets priority. Looking at the statistics, experiment 4 performed best of all experiments. The length of stay of the external trucks fluctuates minimally, which is confirmed by the low variance. It stays between the 4.72 and 6.66 minutes and there is no peak. In *Figure 21*, it can be seen that the peak in length of stay after seven hours that was seen in experiment 1, is not visible anymore in experiment 4.

Furthermore, the GMPH in experiment 4 is higher than in experiment 1 at almost every point in time. During the busiest hours (10 to 12), the GMPH increases with approximately 1.5. The GMPH is 34.3 in the fourteenth hour, which is the highest GMPH that was seen during all experiments.



Statistics

GMPH	
Average	33,24
Variance	0,47
Min	32,00
Max	34,30

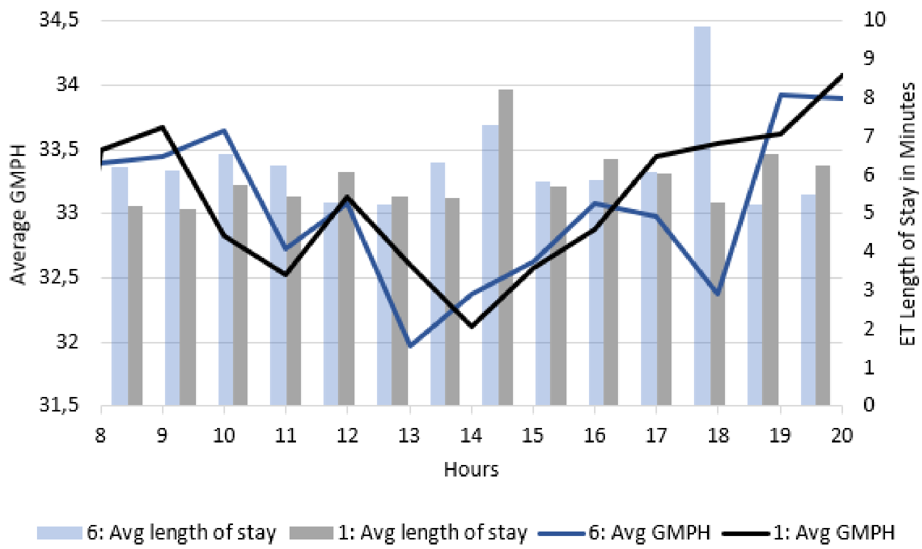
ET Length of Stay (min)	
Average	5,81
Variance	0,28
Min	4,72
Max	6,66

Figure 21: A comparison of experiment 1 & 4

Experiment 6: Minimization of acceleration/deceleration

In experiment 6, the amount of times a vehicle has to accelerate or decelerate is minimized. This is done by giving priority to the vehicle that drives the fastest. In *Figure 22*, the KPIs of experiment 1 (GMPH: black line, Length of Stay: grey columns) and 6 (GMPH: blue line, Length of Stay: blue columns) are shown.

The GMPH of experiment 6 starts approximately at the same value as the GMPH of experiment 1. After three hours, the GMPH starts to decrease fast. After six hours, the GMPH starts to increase again together with the external truck arrival rate. When the external truck arrival rate approaches its peak, the length of stay of the external trucks increases to ten minutes and the GMPH decreases to 32.5. One hour later, the GMPH increases to almost 34 and the length of stay decreases to less than 6 minutes.



Statistics

GMPH	
Average	33,04
Variance	0,37
Min	32,00
Max	33,90

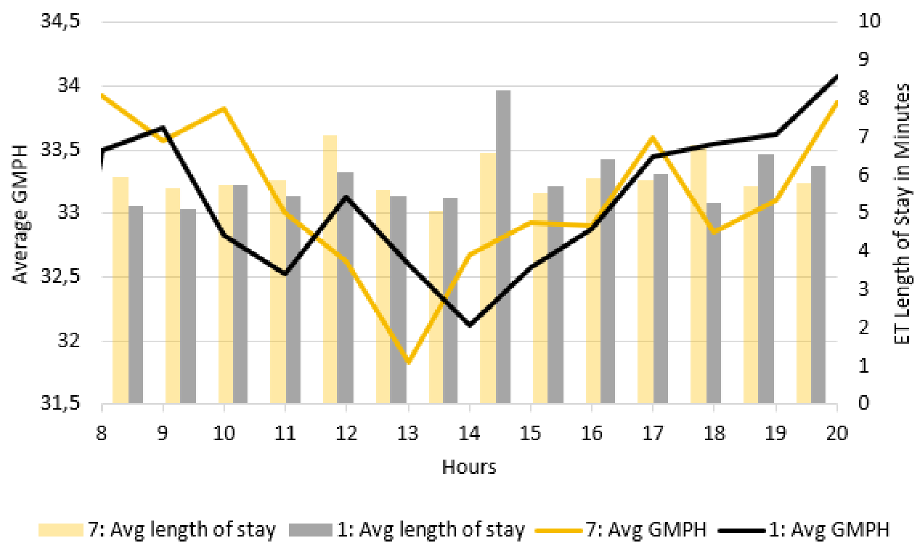
ET Length of Stay (min)	
Average	6,27
Variance	1,52
Min	5,24
Max	9,87

Figure 22: A comparison of experiment 1 & 6

Experiment 7: Priority based on urgency

The last traffic rule that was experimented with was the rule in which priority was given based on the urgency of vehicles. In *Figure 23*, the KPIs of experiment 1 (GMPH: black line, Length of Stay: grey columns) and 7 (GMPH: yellow line, Length of Stay: yellow columns) are shown. After three hours, the GMPH of experiment 6 decreases below 32. After that, it starts to increase until the tenth hour, after that it decreases during the peak of the external truck arrival rate and at the end it increases again close to 34.

The length of stay of the external trucks is relatively smooth. During the 14 hours it stays between the five and seven minutes. After five and eleven hours there is a small peak, but the big peak after seven hours like in the first experiment is eliminated.



Statistics

GMPH	
Average	33,13
Variance	0,37
Min	31,80
Max	33,90
ET Length of Stay (min)	
Average	5,94
Variance	0,30
Min	5,09
Max	7,04

Figure 23: A comparison of experiment 1 & 7

Experiment 8: Combination of the two best rules

The rules with the best averages were Rule 3: Minimization of the expected length of queues and Rule 6: Priority based on urgency. The rules were combined in one last experiment to see whether the combination would yield an even better result. However, the result turned out to be the same as the result that was achieved when only rule 3 was implemented. Those results have already been described and will therefore not be repeated here.

An overview of all experiments

In *Figure 24*, the GMPH of all experiments are plotted per hour. The coloured lines represent the different experiments in the same colours as in the previous paragraphs. The grey area in the background of the graph represents the arrival rate of external trucks.

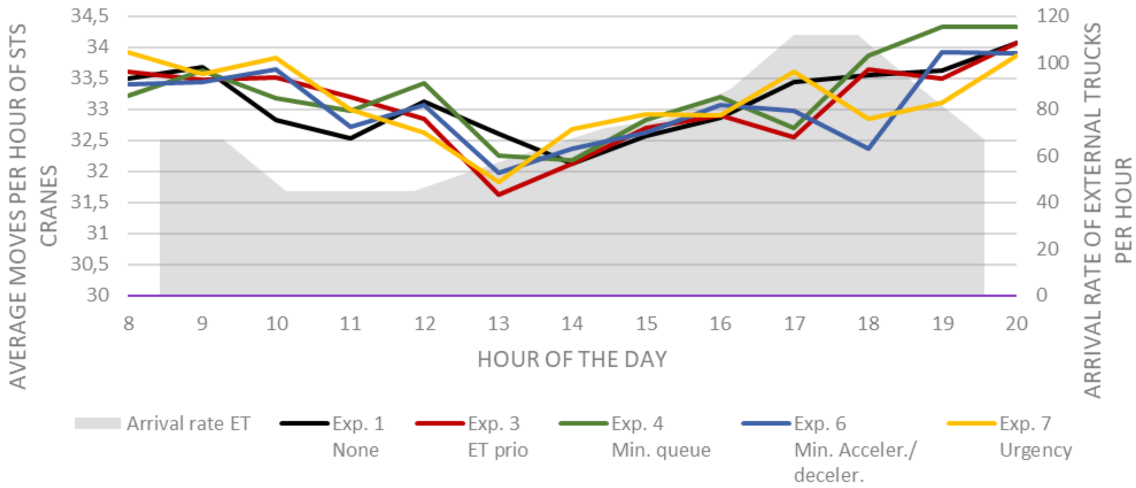


Figure 24: A graph of the GMPH and the arrival rate of the external trucks per hour of all experiments

In the graph it can be seen that the GMPH in all experiments starts between the 33 and 34. In the beginning they fluctuate, but after three hours the GMPH in all experiments decreases. After five hours the external truck arrival rate starts to increase and after six hours the GMPH in most experiments start to increase. When the arrival rate of the external trucks is at its highest (between 17h and 19h), the container terminal is at its busiest. In this part of the graph it can clearly be seen that the GMPH of the experiments start to vary. The arrival rate of the external trucks is at its lowest at the beginning and the end of the day, the GMPH is at its maximum at those points.

8. Discussion

In this chapter, the results that were presented in *Chapter 7* will be discussed. The outcomes of the different experiments will be compared and tested on statistical significance. Possible explanations will be given for particularities and the meaning of the results will be discussed.

The statistics of all experiments are shown in *Table 11*. The best scores are highlighted green and the worst red. In addition to this, the variance is added to be able to see how consistent the rules performed during a day in which the arrival rate of external trucks fluctuates per hour.

Table 11: An overview of the statistics of all experiments

	Gross Moves Per Hour				**Length of Stay External Trucks**			
Experiment:	*Average*	*Variance*	*Min.*	*Max.*	*Average*	*Variance*	*Min.*	*Max.*
1, 2, 5	33.12	0.33	32.13	34.01	5.99	0.65	5.13	8.21
3	33.06	0.47	31.60	34.00	6.00	0.66	4.81	7.68
4	33.24	0.47	32.00	34.30	5.81	0.28	4.72	6.66
6	33.04	0.37	32.00	33.90	6.27	1.52	5.24	9.87
7	33.13	0.37	31.80	33.90	5.94	0.30	5.09	7.04

In *Figure 24*, it was seen that the average GMPH of the experiments varied most between 17h and 19h. In *Table 11*, it can be seen that rule 4 (minimization of the expected length of queues) performed best and rule 6 (minimization of acceleration/deceleration moments) performed worst. To verify whether these differences are of statistically significant importance, a paired samples T-test was carried out in SPSS. To get a first impression, the hours with the biggest differences in GMPH were taken into consideration. This means that the datapoint of 17h - 18h and the datapoint of 18h - 19h are used. Every experiment was completed in 10 runs, so the paired samples T-test consists of 10 datapoints.

To test the statistical significance, rule 3 and rule 6 were both compared with rule 1, which was the base scenario. For both tests, the null hypothesis was devised as follows:

- H_0 : *There is no statistical significance between the base scenario and the scenario with the new traffic rule*

The result of the paired sample t test will be a 95% confidence interval of the difference between the experiments and the p-value. A significance level of 5% is chosen, which indicates a 5% chance that the null hypothesis will be rejected while it should not be. When the p-value is smaller than the significance level (i.e. 0.05), the null hypothesis is rejected. If the p-value is larger than 0.05, the null hypothesis is assumed to be true. In *Table 12*, the results of the paired sample T-tests are shown.

Table 12: Results of paired sample T-tests

Test	**Lower bound of 95%-CI**	**Upper bound of 95%-CI**	**P-value (Sigma)**
Comparing Exp. 1 and 4 ***17h - 18h***	-1.36	0.71	0.497
Comparing Exp. 1 and 4 ***18h - 19h***	-1.74	0.34	0.162
Comparing Exp. 1 and 6 ***17h - 18h***	-0.46	2.81	0.139
Comparing Exp. 1 and 6 ***18h - 19h***	-0.79	0.19	0.200

The full results of the paired sample T-tests are shown in *Appendix F*.

The p-values are all greater than 0.05, which means the null hypothesis cannot be rejected in all cases. This means that for these experiments, no statistically significant difference has been found.

Trends

In *Figure 25*, the average is taken of the GMPH and length of stay of the external trucks per day. The experiments are put in a matrix to show the differences between the averages. Although the results do not show any statistically significant differences between the experiments, it seems the GMPH and the length of stay of the external trucks have a negative impact on each other. When the GMPH increases, the length of stay of the external trucks decrease. For example, experiment 4 has a better average GMPH than all other experiments. However, the average length of stay of the external trucks is longer than in all other experiments. In contradiction to his, the GMPH in experiment 6 is less than all other experiments but the average length of stay of the external trucks is smaller.

Matrix of differences in average GMPH					
	Exp. 1,2,5	Exp. 3	Exp. 4	Exp. 6	Exp. 7
Exp. 1,2,5		-0,06	0,12	-0,08	0,01
Exp. 3	0,06		0,18	-0,02	0,07
Exp. 4	-0,12	-0,18		-0,2	-0,11
Exp. 6	0,08	0,02	0,2		0,09
Exp. 7	-0,01	-0,07	0,11	-0,09	

Matrix of differences in average ET Length of Stay					
	Exp. 1,2,5	Exp. 3	Exp. 4	Exp. 6	Exp. 7
Exp. 1,2,5		0,01	-0,18	0,28	-0,05
Exp. 3	-0,01		-0,19	0,27	-0,06
Exp. 4	0,18	0,19		0,46	0,13
Exp. 6	-0,28	-0,27	-0,46		-0,33
Exp. 7	0,05	0,06	-0,13	0,33	

Figure 25: Matrixes of the average GMPH and length of stay of the external trucks per day

Although it cannot be said that e.g. rule 4 will make the biggest positive difference, it looks like there is a connection between the length of stay of the external trucks and the GMPH. That would mean the crowdedness in a terminal influences the performance of the terminal. Over crowdedness of container terminals could result in ATT delay. In the simulated container terminal, vehicles did not have room to overtake. So, the crowdedness of the container terminal could lead to traffic congestion and more delays.

The difference in the performance of the container terminal between the experiments was small. The biggest difference in GMPH with respect to experiment 1 (i.e. the base scenario) was reached with experiment 4. While these differences have not proven to be statistically significant, it is still interesting to see what such a small difference would save annually.

The average of the GMPH was 0.12 higher than in experiment 1. 0.12 GMPH may not seem as a large difference. However, in *Chapter 2* it was mentioned that an increase of 4 GMPH, would save $800.000 per year. This is equal to €713.149 per year. An increase of 0.12 GMPH per crane would result in *4 * 12 = 0.48* GMPH for this container terminal. That would mean that this rule would save approximately €80.000,- per year compared to giving priority to vehicles from the right.

9. Conclusions

In this last chapter, the outcomes of this research will be described. In *Section 9.1*, a reflection on the core problem is given. In *Section 9.2*, the limitations of this research will be considered. Finally, recommendations for further research will be discussed in *Section 9.3*.

9.1 Conclusion

The core problem that was devised for this research read as follows:

- *'How to design an efficient traffic control system for autonomous vehicles in container terminals with mixed traffic?'*

Because *mixed traffic* is still a new topic, this research was explorative. A traffic control system was introduced that consisted of multiple traffic rules. Experiments were carried out in which the different traffic rules were active. During the experiments, the average of the Gross Moves Per Hour of four STS cranes was measured as well as the length of stay of the external trucks. The rate in which external trucks arrived at the container terminal varied over the day. The GMPH and length of stay were compared regarding each other and the external truck arrival rate.

A lot of research still must be done on this topic before all influencing factors will have been identified. No statistically significant differences were found in this research. However, minimization of the length of stay of external trucks seemed to have a positive impact on the GMPH. This is probably due to the crowdedness of the container terminals. When external trucks have a long length of stay, the waiting times go up and the GMPH decreases.

To design an efficient traffic control system for autonomous vehicles in container terminals with *mixed traffic*, the crowdedness of the container terminal should not be too high. External trucks should get enough priority to keep their length of stay small enough to not overcrowd the terminal. ATTs that are headed to an STS crane that is ready to load or unload should get priority to make sure STS cranes have a high utilization.

ATTs that are going to drive in a *mixed-traffic* container terminal should be able to look far enough ahead to foresee possible conflicts. Especially on intersections they should be aware of approaching traffic. When another rule than priority from right is implemented, the ATTs should be able to look both ways. Furthermore, when traffic rules are implemented and ATTs must be able to distinguish between other ATTs and external trucks, technology must be implemented that can make that distinction.

None of the rules that were investigated in this research proved to perform significantly better than the base scenario. Therefore, an advice on what rules to implement cannot be given. However, the choice what equipment is needed on the ATTs depend on it. For example, to implement the rule that involved the minimization of the expected length of queues, ATTs should know how much vehicles are driving behind them. Therefore, they should be equipped with cameras or sensors at the backside that can see how many vehicles are behind them.

9.2 Limitations

This research focused on designing a traffic control system for intersections in container terminals. The simulation model of the container terminal that was used, was previously built by Distribute. It was not specifically designed to experiment with traffic rules. The vehicles spent approximately 1% of their time at intersections. By changing the traffic control system of those intersections, no statistically significant differences in the performance of the terminal could be made. Ideally, this research would focus on *mixed-traffic* environments with more traffic and intersections. This would lead to higher waiting times and that would offer the opportunity to make more difference by optimizing the traffic control system.

This research was carried out in ten weeks and for that reason there was a limited amount of options that could be tested. All rules have been tested separately, but there was little to experiment with multiple rules per experiment. The experiments took a long time to run. One simulation run had an approximate length of 45 minutes. Therefore, the 8 experiments (base scenario, six different traffic rules and a combination of the two best rules) that were all carried out in 10 runs, took approximately three days to run. Ideally, more runs would have been done to further decrease the relative error. In addition to this, more experiments have to be done to see what factors play the biggest role. Varying the maximum speed of the ATTs, the number of ATTs and the arrival rate of the external trucks are examples of experiments that would offer more insights.

The traffic control options that were assessed had to be implemented in the simulation model and that also took some time. This research was limited to a few traffic control options, while the time it took to implement and compute them was high. Therefore, the most potential traffic control options were implemented and the other options that were found during the literature study were left out of the scope of this research.

The traffic control systems that were implemented in this research focused on ATTs. ATTs communicate wirelessly and if one ATT has to let another ATT pass, it is automatically stopped. In this research, external trucks behaved in the same manner. However, if a traffic control system is to be implemented in a real container terminal, external trucks should get a sign when they must stop e.g. by traffic lights.

9.3 Further research

As stated in *Section 9.1*, a lot of research still must be done before autonomous vehicles can be implemented in *mixed traffic* at a large scale. The research that has been described in this report could be expanded by testing traffic control options with multiple traffic rules. Furthermore, more experiments should be done to exclude certain factors that may also have had influence on the KPIs.

Another option that could be investigated is implementing dynamic traffic control. The traffic control could be adjusted according to the state of container terminals. For example, when the container terminal becomes too crowded with external trucks, external trucks could get priority to decrease their length of stay. On the other hand, when it is not crowded in container terminals, the minimization of expected queue lengths or prioritization based on urgency could be implemented.

When traffic control systems for intersections are implemented in a *mixed-traffic* container terminal, external trucks should get a sign when they have to stop or when they are allowed to cross. Research should be done on what the best ways would be to give these signals to external trucks.

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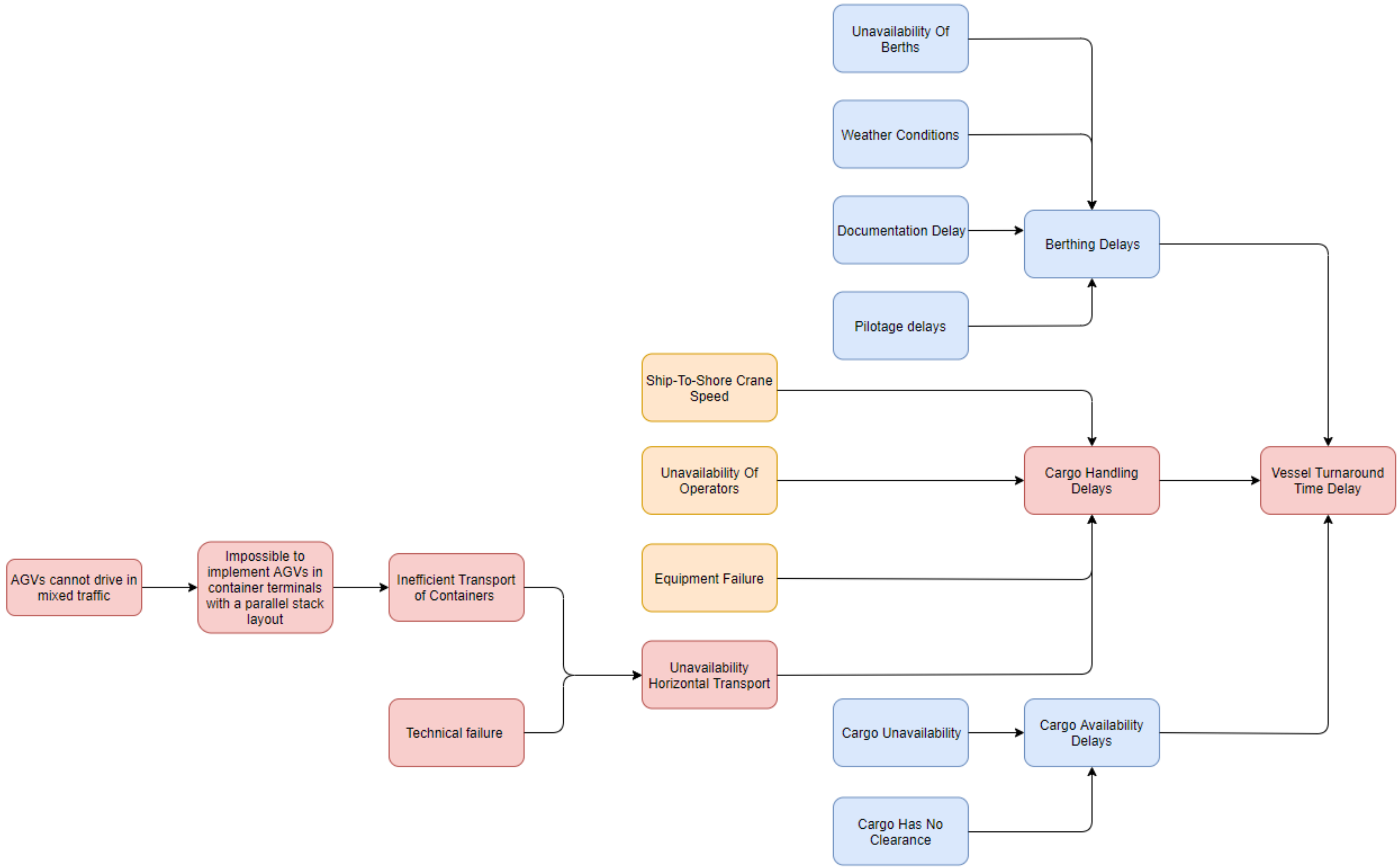
Vasirani, M., & Ossowski, S. (2012). A Market-Inspired Approach for Intersection Management in Urban Road Traffic Networks. *Ournal of Artificial Intelligence Research* , *43*. Retrieved from https://jair.org/index.php/jair/article/view/10759/25695

Vis, I. F. A. (2004). Survey of research in the design and control of automated guided vehicle systems. https://doi.org/10.1016/j.ejor.2004.09.020

Xu, F., Van Brussel, H., Nuttin, M., & Moreas, R. (2003). *Concepts for dynamic obstacle avoidance and their extended application in underground navigation*. *Robotics and Autonomous Systems* (Vol. 42).

Appendices

A. Problem cluster of container terminals with a parallel stack layout



B. Systematic literature review

The following research question was drafted during the research:

- What are options to control traffic in a mixed-traffic environment?

The aim of the systematic literature review is to answer this question by finding a couple of options that could be applied in the simulation model of the container terminal.

The two key concepts from the research question that are determined are:

- Traffic control
- Mixed traffic

Based on these key concepts, a search matrix was devised and is shown in *Table 13*.

Table 13: Search matrix

Constructs	**Related terms**	**Broader terms**	**Narrower terms**
Traffic control	Regulation	Traffic, control	Priority rules, traffic lights
Mixed traffic		Traffic	Autonomous vehicles

Based on the search matrix, a search string was devised. The search string reads as follows:

("traffic control" OR regulation OR control OR "priority rules" OR "traffic lights") AND (mixed-traffic OR "mixed traffic" OR "autonomous vehicles")

The search string was inserted in both Scopus and Web of Science. To narrow down the results, inclusion criteria were used. The criteria are shown in *Table 14*.

Table 14: Inclusion criteria

Inclusion criteria	**Reason**
Title, abstract or keyword must contain 'traffic'	There were too many articles that did not concern traffic in any way and were therefore not of value for this research.
Articles must contain 'simulation' in any way	There were still a lot of articles left and the ones that contain simulation in any way are closer to this research.
Articles must contain 'autonomous' in any way	By applying this criteria, another 15 articles were deleted that were not relevant to this research.

In addition to the inclusion criteria, the exclusion criteria were applied. The exclusion criteria are listed in *Table 15*.

Table 15: Exclusion criteria

Exclusion criteria	Reason
Articles that were published before 1995 were left out	Automated Guided Vehicles were introduced in 1995. The articles that were written before this point in time are not relevant.
Articles that contain 'platoon*' in any way were left out	This is an area where also a lot of research is done in combination with autonomous vehicles. However, it is not of value in this research.
Articles that contain 'sustainability' were left out	A lot of research is done on the sustainable effects of using autonomous vehicles. However, this is not applicable to this research.
Unavailable literature was left out	Literature that was not available because they are behind a paywall or not made available by the author were left out of the end results.
Articles that were written in a foreign language were left out	Articles that were written in foreign languages, such as Chinese, were left out.

The articles that are left were scanned and after this a few articles were removed because they did not fit well enough with this research. After reading the articles another two were deleted. An overview of the systematic literature review can be found in *Figure 26*.

Search protocol for Scopus	**Scope**	**Date of search**	**Date range**	**Number of entries**
("traffic control" OR regulation OR control OR "priority rules" OR "traffic lights") AND (mixed-traffic OR "mixed traffic" OR "autonomous vehicles")	Title, keywords and abstract	26-3-2019	1995 - Now	357
Search protocol for Web of Science				
("traffic control" OR regulation OR control OR "priority rules" OR "traffic lights") AND (mixed-traffic OR "mixed traffic" OR "autonomous vehicles")	Topic (Title, abstract, author keywords and Keywords Plus)	27-3-2019	1995 - Now	264
Total added to Endnote				**621**
Removal of duplicates				-58
Removal of unavailable literature				-27
Removal after applying inclusion criteria				-459
Removal after applying exclusion criteria				-62
Removal after scanning the article				-8
Removal after reading full article				-2
Adding after reading full article				1
Include book (sections)				3
Total selected for review				**9**

Figure 26: Systematic literature review protocol

The articles that were eventually left were analysed and the findings are put in a concept matrix. The matrix can be found in *Table 16*. The methodology of the research in the article is described, the traffic control option that is used and in the last column an explanation of the application is written.

Table 16: Concept matrix

Journal	Author (Year)	Methodology	Operationalization traffic control	Key finding regarding traffic control option
Energies	Astarita, V Giofre, V P Guido, G Vitale, A (2019)	Evaluation of a single intersection scenario by a competition-cooperation diagram	Floating Car Data Adaptive Traffic Signals (FCDATS)	Uses the car-following model of Wiedemann 99 and uses real-time data as input for the FCDATS.
16th International IEEE Conference on Intelligent Transportation Systems	Bento, L C Parafita, R Santos, S Nunes, U (2013)	Testing in an own developed microscopic simulator; ISR-TrafSim	Intelligent Traffic Management (ITM) technique based on spatio-temporal reservation scheme	The traffic is controlled by a 'legacy early method for intelligent traffic management' algorithm. Sensors detect incoming vehicles and the ITM reserves all the possible trajectories in the spatiotemporal matrix.
IEEE Access	Cruz-Piris, L Lopez-Carmona, M A Marsa-Maestre, I (2019)	Testing in a Traffic Cellular Automata (TCA); a microscopic simulator	Optimizing Genetic Algorithms	Obtain optimal arrival patterns; sets of routes and time intervals and determine most efficient use of intersection. Removal of conflict points by rerouting or modifying arrival patterns.
Journal of Artificial Intelligence Research	Dresner, K Stone, P (2008)	Testing in a custom time-based simulator of a multiagent system	Intelligent Transportation Systems (ITS)	Every intersection and vehicle is its own agent. They communicate using a standardized protocol based on a FCFS policy. Vehicles 'reserve' a passage time on an intersection. They cope with non-autonomous agents by including one of these physical traffic light systems: - All lanes from one side have green - One lane has green and the rest of the intersection is free for the autonomous vehicles.
Transportation Research Record	Patel, R Levin, M W Boyles, S D (2016)	Testing in a Dynamic Traffic Assignment (DTA) simulation model	Reservation-based intersection control and reduced following headway	Introduces an intersection manager with which AGVs can communicate wirelessly to make reservations (space-time tiles). To cope with human drivers an app was considered, but traffic lights were implemented.

17th International IEEE Conference on Intelligent Transportation Systems	Qian, X Gregoire, J Moutarde, F De La Fortelle, A (2014)	Testing in a realistic traffic simulator; SUMO	A priority-based coordination system that supports safe passage of legacy vehicles	The distance between a legacy vehicle and an autonomous one should always be the maximal brake distance. Vehicles in front get priority.
International Symposium on Enhancing Highway Performance (2016)	Tettamanti, T Mohammadi, A Asadi, H Varga, I (2017)	Testing in a microscopic simulator	A nonlinear Model Predictive Control (MPC) and car-following method	Outside junctions a car-following method is applied. Within a certain radius of the intersection, an MPC is applied. Objective function is the minimization of acceleration/deceleration.
International Symposium on Enhancing Highway Performance	Wietholt, T Harding, J (2016)	Testing in a microscopic simulator	Traffic management by a dynamic traffic control system (temporary hard shoulder running)	Uses dynamic traffic control to harmonise traffic flow. The system needs cameras, sensors and variable signs to indicate the speed that is allowed in a sector. By looking ahead, the system can determine the perfect speed.
Complex & Intelligent Systems	Wuthishuwong, C Traechtler, A (2017)	Testing in a simulator	A discrete time consensus algorithm to determine the control policy	Proposes an autonomous intersection management; a traffic signal-less system based on V2V, V2I and I2I communication. It is a distributed way of solving conflicts locally.

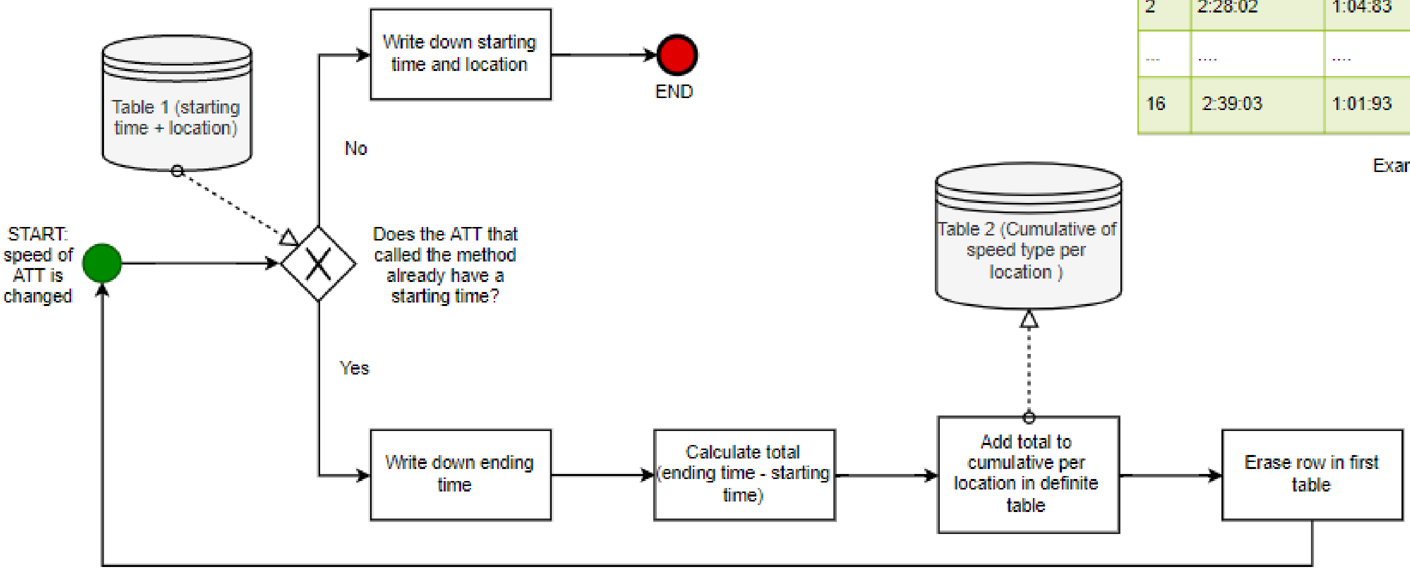
C. Flowchart of the method that records the time division of the ATTs

ATT	Starting time	Ending time	Total	Type	Location
1	2:30:02			Null	STS
2	2:28:02			Reduced	
...	....	....	....	....	...
16	2:39:03			Normal	

Example Table 1

ATT	Normal speed	Reduced speed	Waiting at STS	Waiting at Stack
1	2:30:02	1:03:00	30:03	10:34
2	2:28:02	1:04:83	24:02	15:32
...	....	....	....	....
16	2:39:03	1:01:93	22:01	16:03

Example Table 2



D. Code for recording time division of ATTs

```
param AT: object, PositionAT: string
var row : integer

row := AT.GetNo

if .Models.PSA.ATStatistics["Starting time", row]= void -- check if the autotug already has a starting time
    .Models.PSA.ATStatistics["Starting time", row]:= .Models.PSA.EventController.Simtime -- determine starting time

-- determine speed of the coming period
    if AT.Speed = .Models.PSA.PSA_Input.NormalSpeed and AT.Stopped = FALSE
        .Models.PSA.ATStatistics["Speed", row] := "Normal"      -- normal speed
    elseif AT.Speed = 0 or AT.Stopped= TRUE
        .Models.PSA.ATStatistics["Speed", row] := "Null"        -- standing still
    elseif AT.Speed > 0 and AT.Speed < .Models.PSA.PSA_Input.NormalSpeed and AT.Stopped = FALSE
        .Models.PSA.ATStatistics["Speed", row] := "Reduced"     -- if speed /= null or normal
    else
        debug -- should never be in this situation
    end

    -- if speed is null, check by which method it was done
    if .Models.PSA.ATStatistics["Speed", row] = "Null"
        if positionAT = "BetweenStacks"     -- scenario 1
            .Models.PSA.ATStatistics["Location", row] := "BetweenStacks"
        elseif positionAT = "StackToCrossing"       -- scenario 2
            .Models.PSA.ATStatistics["Location", row] := "StackToCrossing"
        elseif positionAT = "MergingFromStack"      -- scenario 3
            .Models.PSA.ATStatistics["Location", row] := "MergingFromStack"
        elseif positionAT = "WaitForMergingAT"      -- scenario 4
            .Models.PSA.ATStatistics["Location", row] := "WaitForMergingAT"
        elseif positionAT = "HighwayToStack"        -- scenario 5
            .Models.PSA.ATStatistics["Location", row] := "HighwayToStack"
        elseif positionAT = "CheckYellowSensorDist"     -- scenario 6
            .Models.PSA.ATStatistics["Location", row] := "CheckYellowSensorDist"
        elseif positionAT = "CheckForWorkers"       -- scenario 7
            .Models.PSA.ATStatistics["Location", row] := "CheckForWorkers"
        elseif positionAT = "TurnEndOfQuay"     -- scenario 8
            .Models.PSA.ATStatistics["Location", row] := "TurnEndOfQuay"
        elseif positionAT = "WaitingStack"      -- if at Stack Area (called in 'unload')
            .Models.PSA.ATStatistics["Location", row] := "WaitingStack"
        elseif positionAT = "IdlingArea"
            .Models.PSA.ATStatistics["Location", row] := "IdlingArea"
        elseif PositionAT = "WaitingSTS"    --if at STS crane (called in 'QCload')
            .Models.PSA.ATStatistics["Location", row] := "WaitingSTS"
        end
    end

else
    .Models.PSA.ATStatistics["Ending time", row]:= .Models.PSA.EventController.Simtime -- fill in second row with ending time
    -- fill in total by distracting first row of second row
    .Models.PSA.ATStatistics["Total", row]:= .Models.PSA.ATStatistics["Ending time", row] - .Models.PSA.ATStatistics["Starting time", row]
    -- write cumulatives down in totals table
    if .Models.PSA.ATStatistics["Speed", row] = "Reduced"
        .Models.PSA.ATStatisticsTotals["Reduced speed", row]+= .Models.PSA.ATStatistics["Total", row]
    elseif .Models.PSA.ATStatistics["Speed", row] = "Normal"
        .Models.PSA.ATStatisticsTotals["Normal speed", row]+= .Models.PSA.ATStatistics["Total", row]
    elseif .Models.PSA.ATStatistics["Speed", row] = "Null"
        .Models.PSA.ATStatisticsTotals["Null", row]+= .Models.PSA.ATStatistics["Total", row]
    end


else
    .Models.PSA.ATStatistics["Ending time", row]:= .Models.PSA.EventController.Simtime -- fill in second row with ending time
    -- fill in total by distracting first row of second row
    .Models.PSA.ATStatistics["Total", row]:= .Models.PSA.ATStatistics["Ending time", row] - .Models.PSA.ATStatistics["Starting time", row]
    -- write cumulatives down in totals table
    if .Models.PSA.ATStatistics["Speed", row] = "Reduced"
        .Models.PSA.ATStatisticsTotals["Reduced speed", row]+= .Models.PSA.ATStatistics["Total", row]
    elseif .Models.PSA.ATStatistics["Speed", row] = "Normal"
        .Models.PSA.ATStatisticsTotals["Normal speed", row]+= .Models.PSA.ATStatistics["Total", row]
    elseif .Models.PSA.ATStatistics["Speed", row] = "Null"
        .Models.PSA.ATStatisticsTotals["Null", row]+= .Models.PSA.ATStatistics["Total", row]
    end

    -- determine location if AT was standing still
    if .Models.PSA.ATStatistics["Speed", row] = "Null"
        if .Models.PSA.ATStatistics["Location", row] = "BetweenStacks"
            .Models.PSA.ATStatisticsTotals["BetweenStacks", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "StackToCrossing"
            .Models.PSA.ATStatisticsTotals["StackToCrossing", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "MergingFromStack"
            .Models.PSA.ATStatisticsTotals["MergingFromStack", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "WaitForMergingAT"
            .Models.PSA.ATStatisticsTotals["WaitForMergingAT", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "HighwayToStack"
            .Models.PSA.ATStatisticsTotals["HighwayToStack", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "CheckYellowSensorDist"
            .Models.PSA.ATStatisticsTotals["CheckYellowSensorDist", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "CheckForWorkers"
            .Models.PSA.ATStatisticsTotals["CheckForWorkers", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "TurnEndOfQuay"
            .Models.PSA.ATStatisticsTotals["TurnEndOfQuay", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "WaitingStack"
            .Models.PSA.ATStatisticsTotals["WaitingStack", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "IdlingArea"
            .Models.PSA.ATStatisticsTotals["IdlingArea", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "WaitingSTS"     -- determine if AT was at STS crane
        .Models.PSA.ATStatisticsTotals["WaitingSTS", row]+= .Models.PSA.ATStatistics["Total", row]
        elseif .Models.PSA.ATStatistics["Location", row] = "Waiting Misc"
            .Models.PSA.ATStatisticsTotals["Waiting Misc", row]+= .Models.PSA.ATStatistics["Total", row]
        else
            debug
        end
    end
    .Models.PSA.ATStatisticsTotals["Total", row] += .Models.PSA.ATStatistics["Total", row]
    .Models.PSA.ATStatistics.Delete({1, row}..{*, row}) -- delete row from first table
    self.execute(AT, PositionAT) -- calling this method again without starting time
end
```

E. Code for updating the traffic control scores

```
-- determine queues STS cranes and sort them from short to long
STSCraneQueue["STS", 1] := 1
STSCraneQueue["STS", 2] := 2
STSCraneQueue["STS", 3] := 3
STSCraneQueue["STS", 4] := 4

STSCraneQueue["Destination", 1] := .Models.PSA.QuayHighway1_2
STSCraneQueue["Destination", 2] := .Models.PSA.QuayHighway2_2
STSCraneQueue["Destination", 3] := .Models.PSA.QuayHighway3_1
STSCraneQueue["Destination", 4] := .Models.PSA.QuayHighway4_1

STSCraneQueue["Queue", 1] := .Models.PSA.QuayHighway1_2.NumMu
STSCraneQueue["Queue", 2] := .Models.PSA.QuayHighway2_2.NumMu
STSCraneQueue["Queue", 3] := .Models.PSA.QuayHighway3_1.NumMu
STSCraneQueue["Queue", 4] := .Models.PSA.QuayHighway4_1.NumMu

STSCraneQueue.sort(2, "up")

for var i := 1 to TrafficControlScores.YDim
    Vehicle := TrafficControlScores["ATT", i]

------------------------------------------------------------------------------------------------------------

    -- RULE 2 & 3: Determine score ATT & ET prio
------------------------------------------------------------------------------------------------------------
    -- if vehicle is not an external truck: ATT score = 1, ET score = 0
    if vehicle.class /= .ApplicationObjects.Transporters.ExternalTruck
        TrafficControlScores["Score ATT prio", i] := .models.PSA.Experiments["ATT prio", .Models.PSA.PSA_Input.CurrentExperiment] * 1
        TrafficControlScores["Score ET prio", i] := 0

    -- if vehicle is an external truck: ATT score = 0, ET score = 1
    else
        TrafficControlScores["Score ATT prio", i] := 0
        TrafficControlScores["Score ET prio", i] := .models.PSA.Experiments["ET prio", .Models.PSA.PSA_Input.CurrentExperiment] * 1
    end

------------------------------------------------------------------------------------------------------------

    -- RULE 4: Determine score min. queue length
------------------------------------------------------------------------------------------------------------
    .models.PSA.TrafficControl.TrafficControlScores.CursorY := 1
    .Models.PSA.TrafficControl.TrafficControlScores.find(vehicle)

    row := .models.PSA.TrafficControl.TrafficControlScores.CursorY

    ExpectedQueue := 0

    -- determine number of vehicles on all predecessors
    For var j := 1 to vehicle.frontlocation.NumPred
        ExpectedQueue += vehicle.FrontLocation.pred(j).NumMu
    Next

    -- add number of MUs on track of the vehicle
    ExpectedQueue := vehicle.frontlocation.NumMu + ExpectedQueue

    TrafficControlScores["Score min. queue length", row] := .Models.PSA.Experiments["Min. queue length",.Models.PSA.PSA_Input.CurrentExperiment] * ExpectedQueue

    ------------------------------------------------------------------------------------------------------------

     -- RULE 5: Determine score FCFS
    ------------------------------------------------------------------------------------------------------------
     -- Give 'AT' score 1 for FCFS, while that is the first one to enter this loop
     .Models.PSA.TrafficControl.TrafficControlScores.CursorY := 1
     .Models.PSA.TrafficControl.TrafficControlScores.find(AT)
     FCFSScore := .Models.PSA.TrafficControl.TrafficControlScores.CursorY
     .Models.PSA.TrafficControl.TrafficControlScores["Score FCFS", FCFSScore] := .Models.PSA.Experiments["FCFS", 1] * 1

    ------------------------------------------------------------------------------------------------------------

     -- RULE 6: Determine score min. acceler./deceler.
    ------------------------------------------------------------------------------------------------------------
     if Vehicle.Currentspeed ~= .Models.PSA.PSA_Input.NormalSpeed
         TrafficControlScores["Score min. acceler./deceler.", i] := .models.PSA.Experiments["Min. acceler./deceler.", .Models.PSA.PSA_Input.CurrentExperiment] * 2
     elseif Vehicle.Currentspeed = 0
         TrafficControlScores["Score min. acceler./deceler.", i] := 0
     else
         TrafficControlScores["Score min. acceler./deceler.", i] := .models.PSA.Experiments["Min. acceler./deceler.", .Models.PSA.PSA_Input.CurrentExperiment] * 1
     end

    ------------------------------------------------------------------------------------------------------------

     -- RULE 7: Determine score Urgency
    ------------------------------------------------------------------------------------------------------------
     .models.PSA.TrafficControl.STSCraneQueue.CursorY := 1
     findDest := .Models.PSA.TrafficControl.STSCraneQueue.find(vehicle.destination)

     if findDest = TRUE
         TrafficControlScores["Score Urgency", i] := .models.PSA.Experiments["Urgency", .Models.PSA.PSA_Input.CurrentExperiment] * (.models.PSA.TrafficControl.STSCraneQueue.CursorY - 1)
     else
         TrafficControlScores["Score Urgency", i] := 0
     end

    ------------------------------------------------------------------------------------------------------------

     -- DETERMINE OVERALL SCORE
    ------------------------------------------------------------------------------------------------------------
     TrafficControlScores["Overall Score", i] := TrafficControlScores.sum({2,i}..{7,i})

    ------------------------------------------------------------------------------------------------------------
    next

    TrafficControlScores.sort(8,"down")      -- sort on score
```

F. Paired Sample T-Test to compare means

Pair 1: comparing experiment 1 and 4

Pair 2: comparing experiment 1 and 6

Based on 10 datapoints gathered between 17h - 18h

Paired Samples Test

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	NoRule - Min.Queue	-,32500	1,45321	,45954	-1,36456	,71456	-,707	9	,497
Pair 2	NoRule - Min.Acceler. Deceler	1,17500	2,29144	,72462	-,46420	2,81420	1,622	9	,139

Pair 1: comparing experiment 1 and 4

Pair 2: comparing experiment 1 and 6

Based on 10 datapoints gathered between 18h - 19h

Paired Samples Test

		Paired Differences							
					95% Confidence Interval of the Difference				
		Mean	Std. Deviation	Std. Error Mean	Lower	Upper	t	df	Sig. (2-tailed)
Pair 1	NoRule - Min.Queue	-,70000	1,45201	,45917	-1,73871	,33871	-1,525	9	,162
Pair 2	NoRule - Min.Acceler. Deceler	-,30000	,68516	,21667	-,79013	,19013	-1,385	9	,200