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MIXING IT UP: SIMULATION OF MIXED TRAFFIC CONTAINER TERMINALS

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ABSTRACT

The development from a completely manual brownfield terminal towards a highly automated one proceeds in a number of steps. To take the first steps, it is crucial to know how introducing Automated Yard Tractors (AYTs) influences port productivity at Mixed-Traffic Terminals (MTTs). In these terminals, (non-automated) road trucks and yard tractors share the same infrastructure. This paper employs discrete-event simulation in order to analyze the performance of a brownfield terminal where manual yard tractors are replaced by AYTs. The results look promising: high utilization rates are reached in MTTs, with a modest number of AYTs. In fact, these utilization rates are reached with the same number of yard tractors as are typically used in comparable terminals with manually operated vehicles. Special attention is paid to the influence of road trucks on terminal congestion during peak hours.

1 INTRODUCTION

Container terminals worldwide have adopted increasing levels of automated or unmanned systems to increase productivity. In the early 1990s, the first Automated Guided Vehicles (AGVs) were introduced and many related automated systems, such as automated Ship-To-Shore cranes (STSs) and Automated Straddle Carriers (ASCs), have found their way to market, as a strategy to increase operational productivity (Montoya-Torres et al. 2015). Despite the increasing automation levels, port operators struggle to turn around vessels in a timely manner, as vessel size continues to outgrow the increased port productivity, resulting in delays and high penalty costs. A commonly mentioned cause of the lack of performance of highly Automated Container Terminals (ACTs) is the low flexibility of such a, typically centrally controlled, system. Indeed, the intelligence of the automated systems, which should improve productivity, originates from the (central) control system rather than, for example, from the AGVs or ASCs. These kinds of optimization systems are less suitable for real-time decision making in stochastic and dynamic environments, since they typically (i) require a lot of information in advance, (ii) are sensitive to information updates, (iii) are less suitable to respond in a timely manner, and (iv) are not flexible enough to deal with changing environments and situations with multiple autonomous actors (Mes et al. 2007). Therefore, delegation of control might be a key to increase operational performance. Moreover, as ACTs rely on infrastructural requirements (e.g., AGVs are guided using transponders in the ground), highly automated solutions are typically only deployed in greenfield terminals, where automated equipment is strictly separated from manual operations. AGVs are exclusively deployed in so-called perpendicular-oriented terminals, given the orientation of the stacks compared to the shore. The stacks, therefore, create a physical barrier between the automated systems and the manual operations (e.g., road trucks), resulting in a safe and controllable environment. Existing (i.e., brownfield) terminals, however, lack such a physical barrier as many terminals worldwide are parallel oriented (i.e., the stacks are parallel oriented to the shore). Mainly

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due to this layout, adoption of automated vehicles in brownfield terminals is minimal. Currently, manual yard tractors are used in many terminals for loading and unloading containers at both STSs and stack cranes. Recent advances and innovations have created opportunities for brownfield terminals to adopt automated vehicles in the form of Automated Yard Tractors (AYTs). Examples include the Volvo Vera and the Terberg AutoTUG, as illustrated in Figure 1. These AYTs are able to drive unmanned and autonomously. They also offer opportunities to revise the operational control hierarchy, as intelligence can be delegated to the vehicles due to their onboard control systems. Theoretically, AYTs can be deployed in any parallel oriented brownfield terminal, but they also pose additional challenges. In these terminals, (non-automated) road trucks and yard tractors share the same infrastructure. Therefore, introducing AYTs results in a so-called Mixed-Traffic Terminal (MTT). In an MTT, the road infrastructure is shared between AYTs and road trucks. Gerrits et al. (2019a) show how this merging process should be managed in order to create a safe, understandable, and efficient system. Clearly, the development from a totally manual brownfield terminal towards a highly automated one proceeds in a number of steps. To take the first steps, it is crucial to know how introducing AYTs influences port productivity at MTTs. This paper exploits discrete-event simulation in order to analyze the performance of a brownfield terminal by replacing manual yard tractors with AYTs. In that way, we let simulation drive innovation.

The remainder of this paper is structured as follows: Section 2 reviews the literature and states our contribution. In Section 3, the problem setting and a case study are presented. The conceptual model is presented in Section 4 and the simulation model in Section 5. The results are discussed in Section 6. This paper closes with conclusions and directions for further research in Section 7.

Figure 1: Illustration of Automated Yard Tractors (AYTs).

2 RELATED WORK

Literature on ACTs is substantial and simulation is widely used to analyze container terminal operations, as exemplified by the literature review of Dragovic et al. (2017). More specific reviews include topics like smart technologies (Cimino et al. 2017) and future challenges (Kim and Lee 2015). Typically, research areas at container terminals include scheduling and routing (Stahlbock and Voβ 2008; Fazlollahtabar and Saidi-Mehrabad 2015), dispatching (Grunow et al. 2004; Garro et al. 2015), port management (Wibowo et al. 2015), terminal configuration and planning (Sun et al. 2013; Mes and Douma 2016), container stacking policies (Dekker et al. 2007; Park et al. 2011), inter-terminal cooperation (Nabais et al. 2013), yard crane scheduling (Fotuhi et al. 2013; Gharehgozli et al. 2015), transportation systems (Duinkerken et al. 2006), collision avoidance (Marinica et al. 2012), deadlocks (Lehmann et al. 2006), control hierarchies (Zheng and Negenborn 2014) and bay planning (Parthibaraj et al. 2017). Moreover, the impact of AGVs or ASCs has been extensively researched. The interested reader is referred to the reviews of Vis (2006) and Kaoud et al. (2017). However, due to the novelty of AYTs, literature on this topic is rather scarce. Also, as pointed out by McGinley (2014), integrating non-automated and automated cargo handling equipment, as is the case with MTTs, has specific challenges. An exploratory research on the impact of AYTs at MTTs has been presented by Gerrits et al. (2019a). The present paper extends the latter by focusing on the simulation modeling aspects of AYTs and proposes an MTT simulation model, which in itself is an extension of the non-mixed traffic model presented in Gerrits et al. (2019b).

3 CASE DESCRIPTION

To guide the discussion on the impact of mixed traffic at terminals using AYTs, let us focus on the terminal shown in Figure 2. It features a single berth with one vessel, which is served by four STSs. There are twelve stacks to temporarily store containers. Each STS has a dedicated lane for the (un)loading of containers to AYTs. Each stack is serviced by an ASC that interacts with AYTs via a lane at either the top or bottom of the stack. The top six stacks are used to store export (or transhipment) containers and the bottom six for import containers. Furthermore, a commonly used routing system from practice is employed. The AYTs drive underneath the STSs and between the stacks to pick up and drop off containers by following the black lanes. More specifically, between the stacks there are three lanes: two pick-up and drop-off (P/D) lanes underneath the cranes for loading and unloading, and one passageway (Figure 3a). The passageway is used to drive between the stacks. The AYTs switch to a P/D lane from the main passageway, just before their destination. After (un)loading, the AYTs switch back to the main passageway as soon as possible. Road trucks enter the terminal via the entry point at the bottom left of Figure 2. They follow the same lanes as the AYTs through the stacks and leave the system at the bottom right. Road trucks drive to import stacks to pick-up a container and to export stacks to drop-off a container. They follow the same procedure for (un)loading at the P/D lanes as the AYTs. Inherent to this commonly used type of terminal, is that yard tractors and road trucks need to share lanes, resulting in a mixed traffic system. This paper develops a simulation model for this case study to show how AYTs impact port productivity. Simulation is deployed as experimenting with AYTs in actual port operations requires a tremendous effort and is therefore not favorable. First, the conceptual model is presented in Section 4.

4 CONCEPTUAL MODEL

Before presenting the implemented simulation model for our case study, an abstraction is made using a conceptual model. The following elements are described: the inputs (Section 4.1), outputs (Section 4.2), experimental factors used (Section 4.3), and model assumptions (Section 4.4).

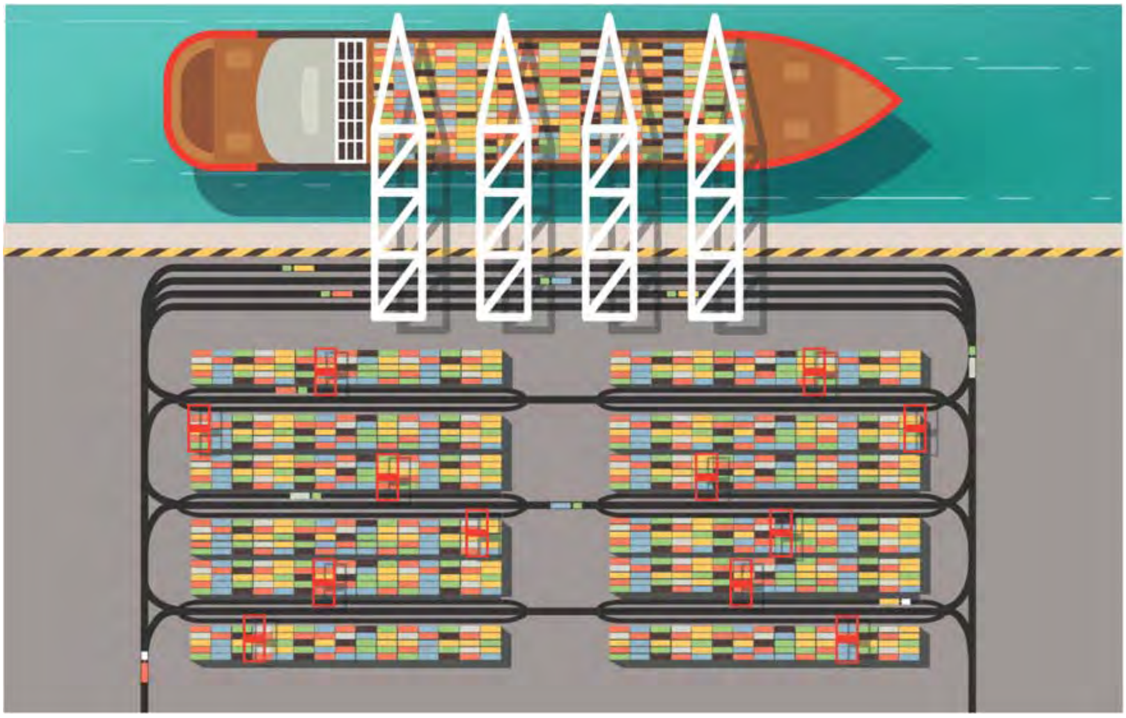
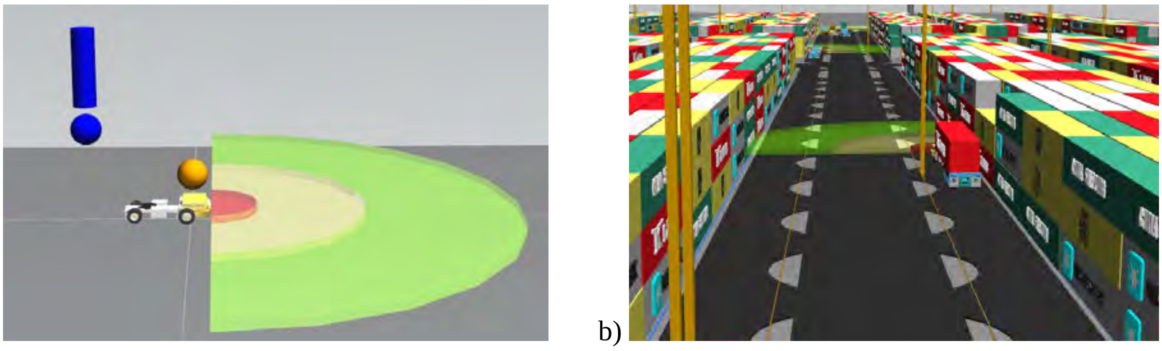


Figure 2: Top-down view of the terminal under consideration.



a) b)

Figure 3: (a) Close-up of the area between the stacks, and (b) visualization of an AYT.

4.1 Input

Regarding the inputs, there is a distinction between (i) the terminal layout and cranes, (ii) the vessel, (iii) the stacks, (iv) the AYTs, and (v) the road trucks.

1. **Terminal layout and cranes.** The terminal has a berth with a certain length and a set of STSs. The time per container load or unload cycle varies in practice. This is modelled by drawing a cycle time from an empirical distribution every time a new cycle starts. The spreader and hoisting speeds are adjusted accordingly to resemble the selected cycle time. The portal speed is also modelled to capture the movements of STSs between the bays of the vessel. The yard area consists of back-to-back stacks, each with a homogeneous capacity. The capacity is determined by the number of containers in the x-, y-, and z-direction. This paper considers standardized 40-foot containers and the use of Rubber Tired Gantry cranes (RTGs). Each stack is initialized with a set of containers to shorten the warmup period. The inner workings of a stack (e.g., reshuffling and job prioritization) are omitted for this study and the stack cranes process jobs first-come-first-serve. Also, for the stack cranes, the portal speed, the spreader speed and the hoisting speed are modelled.
2. **Vessel.** The vessel is modelled as a collection of storage areas, each resembling a single bay. To simplify operations, STSs are dedicated to a set of bays. These sets are disjoint (i.e., two STSs cannot serve the same bay) and are physically separated (i.e., STSs cannot collide). At the initialization, the stowage plan is determined and STSs are assigned to bays. Every bay is randomly chosen to be loading or unloading. The number of load or unload jobs follows a uniform distribution per bay. For scheduling purposes, a schedule-ahead period is used where k containers are scheduled to AYTs in advance.
3. **Stacks.** The stacks are also initialised with containers at the beginning of a run. Each stack has one or more RTGs. Figure 3a depicts the three lanes between the stacks introduced earlier: a passageway flanked by two P/D lanes, which are reachable by all vehicles. Three types of containers are included, which need to be stored in the stacks: import, export, and transhipment. Export and transhipment containers are stacked close to the waterside. Import containers are stacked close to the landside. Given this preference, stacks are chosen randomly for either retrieval or storage. Also, the stack positions where AYTs or road trucks load and unload are selected randomly.
4. **AYT.** The inputs related to the AYTs consist of (i) the number of AYTs deployed, (ii) vehicle dynamics (speed, acceleration and deceleration, normal braking distance, emergency braking distance), (iii) the field of view (FOV), and (iv) the cornering speed. The number of AYTs is an experimental factor and the maximum vehicle speed can be set between zero and the legally allowed maximum speed. For this study, the speed and corresponding vehicle dynamics have been fixed, as a pre-study showed that increasing the vehicle speed is not recommendable from a safety

perspective and has little impact on STS utilization in this use case. Furthermore, increasing the vehicle speed would require a disproportionally large FOV due to the many blind corners between the stacks, resulting in costly requirements for sensors (e.g., lidars). Lastly, the cornering speed of AYTs is modelled, which is dynamically set depending on whether they carry a container or not. The functionality of lidars used on the vehicle is mimicked by defining spherical shapes in front of the AYT to visualize the FOV, as shown in Figure 3b. The green area visualizes the total FOV of the AYT, i.e., the AYT is aware of its surroundings within this green area. The yellow area visualizes the braking distance, i.e., if the AYT senses something in this area it should use the normal brake. The red area visualizes the emergency braking distance, i.e., if the AYT senses something in this area it should immediately use the emergency brake. It is possible to adjust the dimensions of the colored areas to capture the (technical) capabilities of the lidar of the AYT as well as the vehicle kinematics. Moreover, an orange sphere is used to visualize whether an AYT wants to switch from a P/D lane to the passageway between the stacks. When an AYT wants to make this switch, other approaching AYTs and road trucks need to wait on the passageway, similar to how busses have way when their blinker is on. An exclamation mark denotes whether a person is standing near the vehicle to perform twist lock handling. Approaching AYTs need to reduce their speed with a certain percentage for safety reasons. In our approach, the duration of the twist lock handling follows a uniform distribution. Lastly, for every scheduling request, the AYT places a bid to the so-called Scheduling Manager (which is in charge of the stowage plan). This bid is based on (a) the expected time that it takes for the AYT to process the jobs in its current schedule and (b) the driving distance between the destination of the last job in its schedule and the pick-up location of the to-be-scheduled job. The scheduling manager picks the best bid (i.e., in our case the AYT that can process the job the fastest) and assigns the job to that AYT.

5. **Road truck.** Experience from practice shows that the arrival of road trucks is highly stochastic. To realistically model the impact of road trucks and the resulting mixed-traffic system, the arrival distributions per hour of the day and per day of the week are included. These distributions can be set at the beginning of the simulation run. Trucks are randomly chosen to either pick up a container or drop one off. Similarly to AYT, road trucks require twist lock handling, whose duration is also uniformly distributed.

4.2 Output

The simulation model has the following outputs: (i) the utilization rate per STS, (ii) the AYT occupancy and cycle times, (iii) road truck dwell times, (iv) average AYT speed, (v) the degree of traffic congestion, and (vi) the number of times an AYT encounters a road truck. With these outputs it is possible to analyze the dynamics of a mixed-traffic terminal and study the impact of AYTs on port productivity.

4.3 Experimental Factors

Having designed and described a system where AYTs coexist with manual road trucks in a container terminal, the main interest is how introducing AYTs influences port productivity. Therefore, for this first study, the number of AYTs deployed is varied and the other factors of our case study are kept fixed. This has been decided mainly from a practical point of view, as replacing manual yard tractors with AYTs should have minimal requirements for changing the current operations at the terminal. For example, deploying advanced dynamic traffic rules to control crowded areas would require many adaptations to the current processes. Moreover, given the size of our case study, the driving distances are small, and the time spent at junctions is relatively short. Therefore, the impact of (dynamic) traffic rules is expected to be low.

4.4 Model Assumptions

To reduce the complexity of the simulation model, several assumptions are introduced. First, it is assumed that all cranes are fully operational and that any delay due to temporary malfunction is captured in the cycle times used. Also, STSs need to fully load or unload a bay before switching to another one. When loading a bay, it is assumed that the AYTs arrive with containers in the sequence according to the stowage plan. Moreover, the driving and hoisting speed of the RTGs are assumed to be fixed and we omit the reshuffling. Also, the fleet of AYTs is assumed to be homogeneous and always operational, and the battery is never depleted during operations. Lastly, both AYTs and road trucks are assumed to obey the traffic rules deployed, keep a safe following distance, and are not allowed to overtake.

5 SIMULATION MODELING

Based on the case study and the model described, a discrete-event agent-based simulation model is proposed. As stated by Law (2015), discrete-event simulation is suitable to model agent-based systems, as in virtually all agent-based simulation models state changes occur at a countable number of points in time. The simulation model is used to evaluate the performance of port operations when introducing AYTs at brownfield terminals as illustrated by Figure 4. Below, the five main components of our simulation model are described: (i) terminal layout and routing, (ii) vessel, (iii) STSs, (iv) stacks, and (v) AYTs. The model is implemented in the discrete-event simulation tool Plant Simulation. The components are discussed based on the case study and this software, but the modeling approaches are also applicable for other case studies and other discrete-event simulation tools.

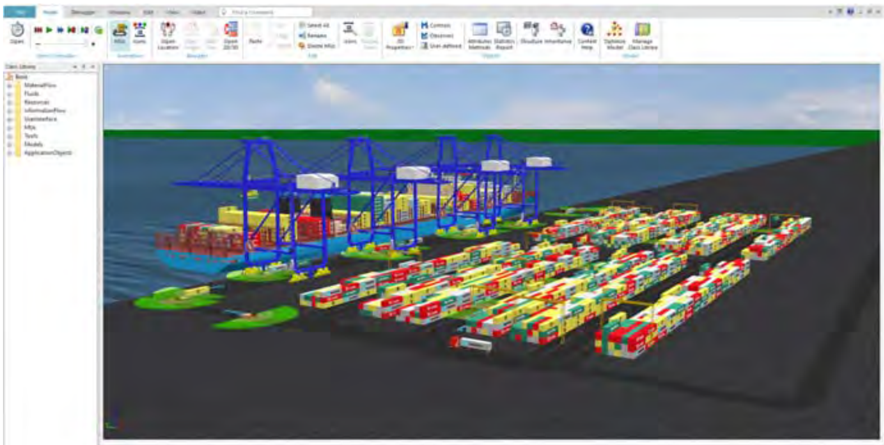


Figure 4: Visualization of the MTT simulation model.

5.1 Terminal Layout and Routing

The infrastructure consists of a set of so-called tracks, which connect the various areas of the terminal. All tracks are unidirectional. Tracks are characterized by length, width, curvature, as well as their predecessors and successors. All tracks are connected with relevant predecessors and successors to create a network for AYTs and road trucks to drive on. With this modeling approach it is also possible to determine traffic rules at junctions (e.g., right traffic has way or the longest queue has way). We use a simple shortest route protocol, which is based on minimizing the length of the set of tracks connecting the origin with the destination. Such a protocol typically comes standard in many discrete-event simulation software packages. In our particular case, this protocol may be tweaked by (dynamically) assigning weights to tracks to penalize the usage of a track (e.g., to select a preferred route from multiple routes with the same distance). This is, for example, useful when AYTs need to take a P/D lane instead of a passageway between the stacks. For every bay of the vessel there is a sensor on the lanes underneath the STSs, in order for AYTs to know where to stop when an STS is serving a particular bay. If there is already an AYT waiting at the STS, other AYTs queue behind it and AYTs are, thus, processed first-come-first-served. Similarly, there are sensors for every P/D position at the stacks on the P/D lanes underneath the RTGs.

5.2 Vessel

The vessel is modelled as a collection of so-called stores that are served by the STSs. Every bay is modelled as a separate store and each store is characterized by its storage capacity in three dimensions. The bays are dedicated to a single STS for loading or unloading. In this way, there are also no possible collisions between STSs, as the bays per STS are physically separated and do not overlap. At the initialization of a simulation run, a bay is randomly selected whether it needs to be loaded or unloaded. Also, the number of jobs per bay is determined, drawn from a chosen distribution. The stowage plan is, thus, fixed at the initialization of every simulation run.

5.3 Ship-To-Shore Cranes

The stowage plans of the STSs are also created at the initialization, and from there on fixed. The set of STSs is modelled using an instance of the MultiPortalCrane (MPC) object of Plant Simulation. Other discrete-event simulation software packages offer similar building blocks. The MPC object is characterized by rail length, rail width and the number of STSs. Each STS is characterized by its dimensions, portal speed, spreader speed, and hoisting speed. The latter three are controlled during the simulation run based on an empirical distribution. That is, a distribution from practice is used to capture – in a single attribute – hoisting dynamics (e.g., influence of wind, tide, STS operator skills, and reachability of containers) and other (difficult to model or quantify) factors. Moreover, it is also possible to define control failures per STS to model large disruptions in the loading or unloading process. To dispatch AYTs to STSs, a scheduling manager is implemented per STS. The AYTs are scheduled by using a fixed look-ahead period. For example, when the look-ahead period is set to k containers and an STS starts the n^{th} job of its schedule, it already requests an AYT for the $(n+k)^{th}$ job. This is particularly useful when an STS is loading the vessel, as the AYT first has to pick up a container at the stack before it can be delivered to the STS. Depending on the size and dynamics of the terminal under consideration, the value of k may be changed to avoid arrival delays, balancing early arrivals (or queue build-ups), and late arrivals.

5.4 Stacks

The terminal features twelve stacks and each stack is characterized by its dimensions and corresponding storage capacity in three dimensions. The stacks are modelled as a combination of a store and an MPC, where every stack is a separate instance containing one RTG and one store. Similarly to the bays, the stacks are characterized by their storage capacity in three dimensions. The RTG is modelled similarly to the STS. The stacks may be filled with containers at initialization to reduce the warmup period.

5.5 Autonomous Yard Tractors

The AYTs are modeled as standard Transporter objects. They are characterized by dimensions, speed, acceleration, deceleration and energy consumption. The container chassis is modelled as a separate transporter that is hitched to the AYT, i.e., it automatically follows. The standard object is expanded in several ways to (more) realistically model autonomous driving. For example, a FOV is added to model lidar functionality, including object detection within this FOV. When something is detected, the AYT needs to slow down for safety reasons.

6 NUMERICAL EXPERIMENTS

This section presents the simulation results of the case study under consideration. First, the experimental design is discussed in Section 6.1. Then, the results are presented in various sections: the average utilization of STSs (Section 6.2), the AYT occupancy (Section 6.3), terminal congestion (Section 6.4), impact of road trucks on port productivity (Section 6.5), and the dwell times of road trucks (Section 6.6).

6.1 Experimental Design

To evaluate the impact of AYTs, there is a specific focus on the vehicles, and the other (related) terminal operations are fixed. Specifically, the experiments focus on a fleet size of 24, 28, 32, and 36 AYTs to serve the four STSs, which is a commonly used range in practice for the number of vehicles deployed. Each experiment consists of a 24-hour run, where the first hour is used as the warm-up period, as determined by using the Welch Method. Five replications are used for each experiment, resulting in a relative error of at most $\gamma = 0.01$ using a significance level $\alpha = 0.05$. The specific values for the inputs, as described in Section 4, are obtained from a terminal operator. For an overview of the input parameters and their values (Table 1).

Table 1: Input parameters and their values.

Input	**Value**
Terminal layout and routing-related	
Berth length (meters)	500
Routing protocol	Shortest path
Traffic rule	Right traffic has way
Stack-related	
Number of stacks	12
Stack orientation	Back-to-back
Number of RTGs per stack	1
Number of P/D locations per stack	15
Stack capacity	450
Initial containers per stack	270
Import containers (%)	40
Export containers (%)	40
Transshipment containers (%)	20
RTG portal speed (m/s)	2
RTG spreader speed (m/s)	1
RTG hoisting speed (m/s)	0.7

Input	**Value**
AYT-related	
Number of AYTs	6-9 per STS
Twist lock handling (seconds)	U~(20,30)
Speed reduction when worker detected (%)	50
Road-truck-related	
Arrival intensity (trucks per hour)	6-67
Pick-up / drop-off distribution	50/50
Number of trucks allowed	Unlimited
Twist lock handling (seconds)	U~(60,120)
Vessel-related	
Number of bays	19
STS-bay assignment	Dedicated
Load/unload distribution	50/50
Number of (un)load jobs per bay	U~(150,250)
Schedule ahead period	5
STS-related	
STS cycle time (seconds)	45-270
STS portal speed (m/s)	1.3
STS lane assignment	Dedicated

6.2 STS Utilization

The STS utilization is the main key performance indicator of port operators and, thus, the adaptation of AYTs highly depends on this metric. Table 2 shows the average realized utilization over all four STS cranes.

Table 2: Results for STS utilization.

Number of AYTs deployed	**STS utilization (%)**
24	82.2
28	86.6
32	88.9
36	89.4

From these results it can be seen that a utilization close to 90 % can be reached with a fleet size of 32 and 36 AYTs. When increasing the number of vehicles further, the increase in STS utilization is negligible and not worth the investment costs. Given the relatively low speed of the AYTs and the need to cope with mixed traffic, this result looks promising as high utilization rates are reached in MTTs with a modest number of vehicles. In fact, a high utilization is reached with the same number of vehicles as typically used in terminals with manually operated vehicles. This is an important driver for port operators to ensure that when introducing AYTs, port productivity, measured in STS utilization, is maintained with the same or a lower number of yard tractors.

6.3 AYT Occupancy and Cycle Time

Besides STS utilization, the occupancy of AYTs is also relevant, as port operators typically want to balance the number of vehicles deployed and crane utilization. The cycle time is the time it takes for an AYT to process one job and consists of the elements in columns 2–6 in Table 3. From this table it can be seen that the portion of free-flow traffic (i.e., driving at maximum allowed speed) decreases when the number of AYTs increases. Simultaneously, driving at reduced speed (e.g., approaching a blind corner or in the proximity of a worker) goes up slightly with more AYTs. Interestingly, the percentage of time waiting at the STSs goes up fairly steep when moving from 24 to 32 AYTs, but this effect diminishes with a further increase. From these results, it can be concluded that the proportionality of the parts of the cycle time (corresponding to columns 2–6 in Table 3) converges at 32 to 36 vehicles. Thus, for our case study, a good balance between STS utilization and number of AYTs lies around 32 vehicles, as increasing the number of vehicles only increases the AYT cycle time (and, thus, a more congestion-sensitive system), without much increasing the STS utilization.

Table 3: Results for AYT occupancy and cycle time.

Number of AYTs deployed	Driving at max. speed (%)	Driving at reduced speed (%)	Waiting at STS (%)	Waiting at stack (%)	Congested (%)	Average cycle time (minutes)
24	31	21	20	18	10	9.7
28	27	20	26	16	11	10.8
32	22	17	32	14	15	12.0
36	20	18	33	14	15	13.1

6.4 AYT Speed and Terminal Congestion

To study the specifics of terminal congestion and AYT cycle time, a heatmap of the average AYT speed is shown in Figure 5. Green areas denote free-flow traffic, whereas red areas denote highly congested areas. At the top part, it can clearly be seen that there are four congested areas, one per STS, as AYTs stop and wait there. At the top left there is also a fairly congested area, as four lanes are merged into one. As only AYTs are allowed to drive there (i.e., non-mixed traffic), this is an interesting area to see whether more-advanced traffic rules are effective. The P/D lanes between the stacks are heavily congested (e.g., waiting for the RTG and waiting to be able to switch to the main passageway), and the same holds for the junctions at the beginning and end of the stacks. As the junctions are mixed-traffic, special attention should be put here in deploying a mixed-traffic terminal both for safety reasons and for port productivity, as these junctions are subject to congestion and, thus, potential productivity loss.

6.5 Impact Degree of Mixed-Traffic on Port Productivity

Another important aspect of this study is how the degree of mixed-traffic influences the port productivity. This is studied by varying the arrival intensity of (manual) road trucks, fixing the number of vehicles deployed, and analyzing the STS utilization per hour throughout the day, as shown in Figure 6. The STS utilization is shown on the primary axis and the arrival intensity of road trucks on the secondary axis (also shown as a yellow surface).

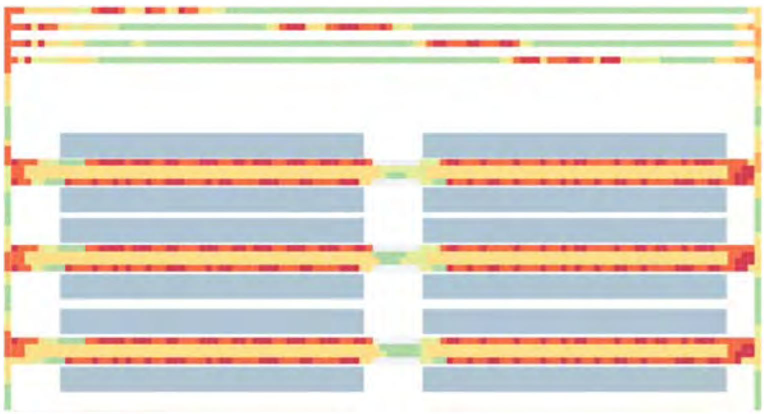


Figure 5: Heatmap of the terminal, expressed in average AYT speed.

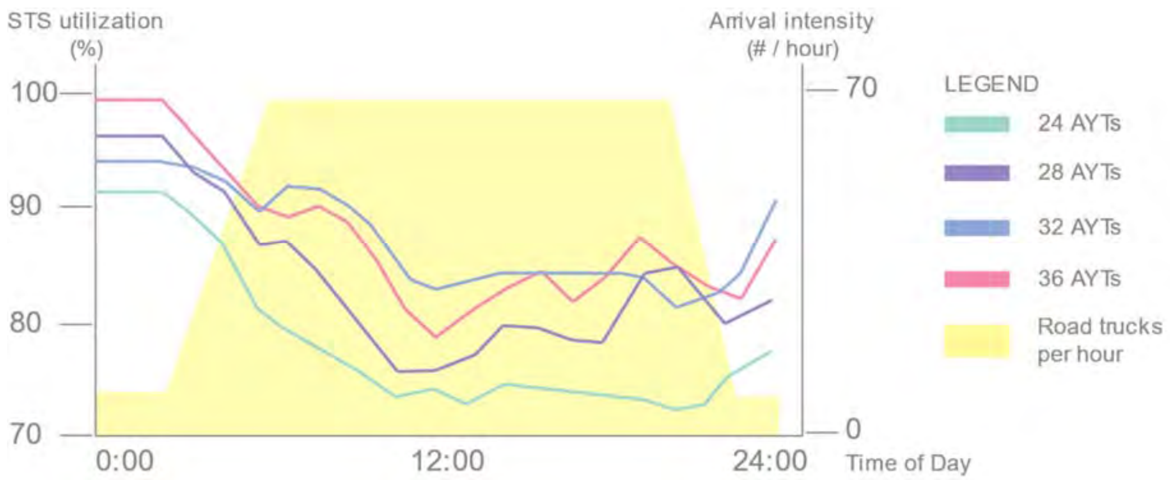


Figure 6: Impact on STS utilization during the day.

From this figure a clear drop is seen in port productivity when the number of road trucks increases. Although such a pattern is also typical for manually operated terminals, mixed-traffic terminals should pay special attention to the influence of road trucks. Even though the STS utilization may be acceptable on average over the day with AYTs, when during the day highly congested areas emerge, this may result in safety issues. Potential deadlocks or unwanted behavior from road truck drivers may then occur. Furthermore, it can be seen that increasing the number of AYTs is more robust against productivity loss. However, 32 AYTs instead of 36 AYTs tend to be more robust, mainly because less congestion is possible with fever vehicles, on top of the reasons discussed in Section 6.4. For port operators, it may be wise to regulate the arrival intensity of external trucks to (i) diminish the negative impact on STS utilization and (ii) provide a more robust and safe solution for an MTT.

6.6 Road Truck Dwell Times

Finally, the effect of the number of AYTs deployed is studied on the road truck dwell times. Combining the results from Table 4 with Section 6.2, it may be concluded that congestion influences AYT cycle time more than it influences road truck dwell time. This can be explained by the fact that congestion for road trucks mainly occurs when (many) STSs are loading the vessel, causing AYTs to visit the specific stacks where road trucks come more frequently. For manual terminals this is less problematic, as manual drivers can easily overtake or take a short cut. AYTs are more restrictive from a safety perspective and do not allow for this kind of behavior. Thus, avoiding to visit the same stacks by both AYTs and road trucks simultaneously might be a fruitful endeavor to increase safety and port productivity.

Table 4: Influence of the number of AYTs on road truck dwell time.

Number of AYTs deployed	**Average dwell time road trucks (minutes)**	**Minimal dwell time road trucks (minutes)**	**Maximum dwell time road trucks (minutes)**
24	8.1	6.5	8.6
28	8.2	7.1	8.9
32	8.8	7.5	9.6
36	9.0	8.1	13.2

7 CONCLUSIONS

This paper employs simulation to analyze the performance of a brownfield terminal where manual yard tractors are replaced by Autonomous Yard Tractors (AYTs). High utilization rates are reached, with a modest number of AYTs, comparable to the amount of yard tractors typically used in manually operated terminals. Similarly to manually operated terminals, a drop in port productivity is seen when the number of road trucks increases. For mixed-traffic terminals it is crucial to regulate the arrival intensity of road trucks. Further research directions include: (i) study the effects of vehicle speed on STS utilization and congestion in larger terminals, (ii) development of communication protocols between AYTs and road trucks, (iii) study the impact of pre-gate controls on terminal congestion and truck waiting profiles, and (iv) study the impact of gradually replacing manual yard tractors with AYTs to evaluate the learning curves for both vehicles so as to guarantee proper coexistence.

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