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ORIGINAL ARTICLE

Advances in terminal management: simulation of vehicle traffic in container terminals

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Abstract
Controlling and managing traffic flows on internal roads in container terminals are crucial in achieving expected productivity levels and reducing negative externalities caused by congestion inside and outside the terminal areas. This paper proposes a simulation approach which terminal operators can use as a decision-support tool to assess the effects of their management strategies and improve terminal performance, resilience, and sustainability. A microscopic traffic simulation approach models key operations of a typical container terminal affecting road traffic flows. In particular, to estimate quantitative indicators, an import truck process is reproduced, considering the overlapping of the external truck and internal trailer flows. To measure environmental impacts, the model is extended with an instantaneous emissions model linked directly to the step-by-step traffic data. The proposed method is tested on a sector of the PSA Genova Pra', the main Italian container gateway terminal. Performance indicators related to the terminal's efficiency and sustainability are estimated, to compare alternative scenarios considering possible operational configurations and disturbance events, such as the closure of a part of the yard. By focusing on the interactions between vehicle flows and terminal equipment operations, this approach offers a new perspective on terminal operations, oriented both towards container terminal operators and stakeholders, such as road hauliers.

Keywords Traffic flows · Micro-simulation model · Container terminals · Negative externalities · Traffic congestion

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1 Introduction

One of the main challenges of container terminals today is managing and controlling vehicle traffic flows. This is due to several factors, such as the increasing quantity of goods handled by seaports, not unrelated to the dynamics imposed by naval gigantism. This phenomenon concerns the continuous growth of vessel capacities, mainly driven by shipping companies pursuing economies of scale. Larger vessels usually bring increasing quantities of containers to ports (call size) to be handled in short intervals (1–2 days) (Haralambides 2019). The new generation of ultra large container vessels (ULCV) are designed for a capacity of 24,000 TEUs and according to the experience of PSA Genova Pra' container terminal, call sizes of up to 7000–8000 containers are expected to be handled, a volume three times higher than 20 years ago. This forces container terminals to improve planning capabilities and efficiency. If not properly managed, container demand peaks can easily lead to congestion and saturation problems inside the terminal, with repercussions on productivity and efficiency. For example, the size of containerships influences negatively the productivity of quay cranes in marine terminals, and this is modelled by a linear relationship, including yard congestion (Jeong and Kim 2024). Outside the terminal, impacts are felt in the surrounding areas and in the forwarding of goods inland. These days, the environmental impacts of congestion and road traffic are concerns very high on the political agendas. When a port's connectivity to external transport systems is provided by road transport, terminals need to handle a huge number of trucks that have to pick up and deliver containers in very short time intervals. The fluctuation and unpredictability of truck arrivals complicate matters. Traffic congestion is one of the main bottlenecks at container terminals that can affect their capacity and performance (van Battum et al. 2023).

In recent years, following the COVID-19 pandemic, the model of global supply chains and just-in-time systems that have driven globalization in the past decades have been called into question. There has been a slowdown in logistics operations and a reduction in the quality of maritime services. The reliability rate of liner shipping services dropped from 78% in 2019 to 35.8% in 2021. The low service quality resulted in vessel delays, cancellations of scheduled departures (blank sailings), port congestion, and empty containers available for export (SRM 2022). Since 2020, the container shipping market has been growing again, and traffic is expected to grow by about 4 per cent annually in the current decade (2020–2029) (Haralambides and Gujar 2023). However, the current environment, called the "new normal" by Haralambides and Gujar (2023), has changed and could be described as volatile, uncertain, unreliable, complex, and ambiguous. Indeed, one just needs to think of the very recent (2024) Red Sea crisis, which has impacted maritime traffic by causing, among other things, route changes and longer delays (Notteboom et al. 2024). In this context, it is crucial to have flexible and resilient terminals to reduce congestion and bottlenecks, making the entire logistics chain efficient and smoother.

1.1 Objective of the study

Road congestion inside and outside port terminals is generated by trucks approaching the terminal to pick up and/or deliver containers. When the terminal is internally congested by road traffic flows, terminal performance deteriorates rapidly, and the low quality of service has a strong impact on the various port stakeholders, mainly terminal operators, trucking companies, and the local community. As far as terminal operators are concerned, high traffic levels raise safety issues as they increase the risk of traffic accidents inside the terminal. Yard road capacity saturation can affect the productivity and efficiency of terminal operations by increasing dwell times and reducing the terminal's handling capacity, placing limits on growth. In general, high levels of congestion within the container terminal reduce the competitiveness of terminal operators.

For the local community, inside and outside traffic congestion leads to several negative externalities caused by the internal combustion engines commonly used for heavy-duty vehicles, especially CO_2 emissions, other pollutants, and noise. Traffic-flow inefficiency also impacts the entire supply chain, causing longer delivery times for goods, translating into higher product prices for customers.

Road congestion also affects trucking companies, as long waiting times reduce productivity and profit margins. Indeed, when the level of terminal services decreases, hauliers' frustration increases as they are forced into long queues, increasing their waiting times.

For all the above reasons, traffic-flow management, even inside closed systems like ports, requires accurate observation of processes to identify critical points and test control actions. In this context, building a simulation model that can reproduce the system's key elements can support selecting and refining the most suitable action according to the expected results.

This study aims to provide a methodological approach based on the modelling and simulation of road traffic flows inside container terminals using the microscopic traffic simulation tool Aimsun®. Vehicles are tracked step by step along with their routes in the terminal while performing their loading and unloading operations. Although the simulation tool used is widely adopted to describe road transport systems and various vehicle types, in this study, the elements already available to build the model were adapted to properly reproduce the key elements of yard and quay crane operations in the terminal. An interesting outcome of using a microscopic traffic simulation that explicitly reproduces vehicle interactions on shared road sections, including congested situations, is estimating fuel consumption and emissions. The final aim is to test the impact of different scenarios of operation events on the efficiency and sustainability of a terminal. The proposed framework was applied to the congested situations observed at the PSA Genova Pra' container terminal in the Italian port of Genoa. The impact of different management strategies for truck operations, including a partial closure of a terminal block, was assessed according to the point of view of three different stakeholders: trucking companies (interested in reducing truck turnaround times and delays), terminal operators (aimed at increasing their productivity) and the local community (to reduce externalities).

1.2 Related works

While much research has addressed the problem of traffic flows (cf. Medina-Salgado et al. 2022; Wang et al. 2022; Zhang et al. 2022), several studies specifically address the problem of modelling and simulating road traffic flows in logistics nodes, such as container terminals (Carlo et al. 2014a, 2014b) or logistics nodes of road haulage. Although many port simulation models in the literature aim to represent vessel arrivals in seaports and related processes (Bellsolà Olba et al. 2018), our paper focuses instead on the land side of container terminals. As emerged from the review on container terminal operations presented by Weerasinghe et al. (2024), few works only deal with problems from an integrated point of view, for example, by evaluating the scheduling of both internal and external trucks considering indicators such as turnaround time or vessel berthing time. Li et al. (2022) proposed a new three-level queuing model for different types of truck movements (delivery, pick-up, and dual transactions) to optimize the utilization of yard handling equipment. Neumann (2007) used a traffic-logistics simulation tool to enable the simulation of internal and external material and information flows. Li et al. (2016) proposed a hybrid simulation model that combines traffic-flow modelling and discrete-event simulation to plan port landside traffic flows and assess traffic conditions under different scenarios, applying it to a real bulk cargo port. Karafa (2012) developed a traffic simulation model to measure the impact of various gate strategies on congestion at terminal gates. Abourraja et al. (2022) built a simulation model based on a distributed architecture to evaluate handling capacity under different scenarios for trailers and export-lorry flows. Petering (2009) used a discrete-event simulation model to assess the effects of block width and storage yard layout on the performance of a maritime terminal, also analysing traffic jams inside the terminal. Lau and Lee (2008) developed a simulation model that integrates the traffic-flow control of internal trailers and the berth operations of a container terminal; terminal operations are modelled using the discrete-event simulation tool AutoMod, with the final objective of evaluating the performance of the berth and reducing traffic congestion problems of a container terminal. Other papers have integrated a macroscopic simulation model, which simulates terminal operations, with a microscopic simulation model that simulates traffic networks adjacent to the terminals, to assess aspects such as the costs associated with processing containers within the terminal (Abadi et al. 2009) or to quantify the movements of empty containers (Chang et al. 2009).

If not properly managed, road traffic flows may produce negative impacts such as congestion, pollution, reduced terminal productivity, and truck service levels. Ambrosino and Caballini (2014) addressed the problem of minimizing truck service times at container terminals while respecting certain congestion levels. Disruptions may represent a cause of congestion in container terminals, and to minimize the negative effects caused by unexpected events, resilience and flexibility should be enhanced. Carboni and Deflorio (2020) used a micro-simulation approach to evaluate selected Key Performance Indicators (KPI) in critical scenarios such as the temporary unavailability of a gantry crane. However, only one process with multiple cranes was considered in the simulated layout, limiting the interactions between truck flows. Burgholzer et al. (2013) presented a traffic micro-simulation model to analyse an intermodal transport network in the case of disruptions. Although different modes were included in the model for Austria, the focus was on the road network connecting terminals, which were modelled as simplified nodes.

To tackle the issue of congestion inside and outside container terminals, several solutions may be implemented. The use of truck appointment systems (TAS) to better manage and control road traffic flows is a possible and profitable mitigation strategy Neagoe et al. (2021). TAS enable the reduction of negative externalities such as congestion, accidents, and pollution, while at the same time, allowing better terminal planning and increasing productivity as well as improved truck turnaround times and service levels (see for instance Abdelmagid et al. 2022; Ambrosino and Caballini 2014; Giuliano and O'Brien 2007; He et al. 2023; N. Li et al. 2018). Caballini and Sacone (2021) simulated various algorithms implementing a truck management system, to reduce congestion outside and inside a marine terminal.

Another important aspect of congestion is the environmental impact (Esmemr et al. 2010; Heinold and Meisel 2018; Karafa 2012; Kelle et al. 2019; Pagea et al. 2007). Grubisic et al. (2020) presented a micro-level traffic simulation model to identify the critical parameters that cause negative environmental externalities both on present and future traffic demand. Also, Nesamani et al. (2017) proposed a micro-simulation model to examine the influence of road section emission-specific characteristics on vehicle operation. Tao et al. (2023) proposed an integrated planning problem of truck operations and storage allocation to minimize the travel distances of trucks, thus reducing pollutant emissions caused by them and traffic congestion. Efficiency and environmental evaluations are also the objectives of Karakas et al (2021), who proposed a discrete Monte Carlo simulation to model a container terminal in different operating scenarios. Despite using a simplified approach based on average values, our paper evaluates time efficiency and carbon footprint, considering similar elements such as queues in quay and yard cranes.

The main contribution of this study is the adaptation of the typical traffic micro-simulation elements, usually used to model traffic flows on roads, to describe and analyse the congested flow of trucks in container terminals, where traffic conditions derive from specific operations performed by different vehicle types. Indeed, in a terminal, not only do external trucks use the road lanes, but internal trailers do, too, generating traffic phenomena. Using existing traffic simulation tools, this modelling approach for container terminals has not yet been adequately exploited. A typical traffic micro-simulation tool is used in this research, since it has been specifically designed, extensively calibrated, and validated to simulate traffic conditions and vehicle interactions, providing levels of reliability of the results that another hand-crafted tool would not provide. The use of proven simulation tools, albeit in other contexts, allows, for example, the use of reliable emission models because they are calibrated with extended datasets and permit good transferability of the method. The methodological approach presented here may support the terminal operator in reducing congestion and pollutant emissions by adopting a different perspective: the focus is, in fact, on the flow of vehicles and not on classic terminal entities used for transportation activities (such as quay cranes, internal trailers, and yard cranes).

The rest of the paper is divided as follows. Section 2 describes the problem of managing road traffic flows in maritime container terminals, and Sect. 3 describes the case study. Section 4 presents the methodology used to simulate traffic flows in this terminal and the KPIs used to assess the simulation outcomes. Section 5 describes the results obtained by applying the proposed method to the case study, whereas Sect. 6 discusses some insights into the proposed approach. Conclusions and future research ideas are outlined in Sect. 7.

2 Problem description

The problem under study concerns modelling road traffic flows in a maritime container terminal to assess the impact of truck traffic flows on terminal productivity, truck turnaround time, congestion, and environmental emissions.

Figure 1 shows the scheme of an import truck cycle in a generic maritime container terminal. The yard is divided into two main areas: one is dedicated to import flows, i.e. containers that are unloaded from ships to continue their journey inland by road or rail, while the other flow is for export containers that arrive at the terminal by truck or train to be loaded onto ships. Export areas are usually near the quay, whereas the import blocks are closer to the truck gate and the inland rail park. Each terminal has a certain amount of equipment (such as trailers, quay cranes, straddle carriers and yard cranes) used to properly perform the intermodal import and export cycle.

When analysing the import cycle, two main traffic flows operate simultaneously in the terminal (Fig. 1):

- Vessel discharge flow (VS): internal trucks (i.e. trailers) go to the assigned quay crane to pick up the container (#1 of Fig. 1). Once it has been picked up (#2 of Fig. 1), the trailer brings the container to the yard; when the trailer arrives in the

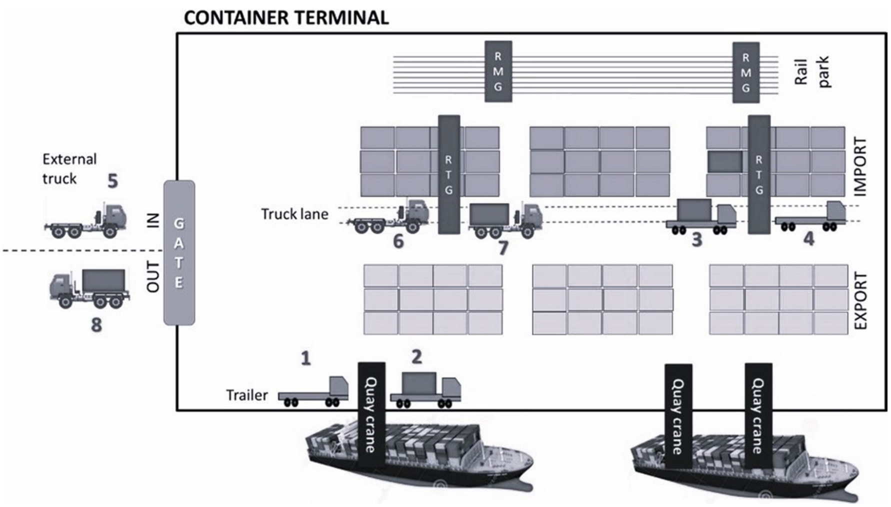

Fig. 1 Scheme of a truck cycle for importing containers in a maritime container terminal

assigned block, it waits in the truck lane for the yard crane to pick up the container (#3 in Fig. 1). After the container has been delivered to the proper yard slot (#4 in Fig. 1), the trailer returns to the quay area and cyclically repeats the above tasks.

- Truck delivery flow (TR): once the container has been stored in the yard to be subsequently forwarded inland, an external truck can arrive to pick it up. The external truck enters the terminal from the gate (#5 in Fig. 1, gate-in) and reaches the assigned yard block (#6 in Fig. 1). Here, the yard crane releases the container onto the external truck (#7 in Fig. 1), which can then exit the terminal (#8 in Fig. 1, gate-out) to take it to its final destination.

Note that the flows described above do not change as the terminal equipment changes. Furthermore, the marine terminal shown in Fig. 1 has an Asian layout Carlo et al. (2014a), where external trucks and internal vehicles (i.e. trailers) move within the same terminal roadway. In this case, the management of heterogeneous traffic flows involves greater complexity. In contrast, the internal and external truck routes are separated in a European layout, making their management much simpler.

Road congestion inside and outside the terminal can depend on the handling pattern and characteristics of the two traffic flows, VS and TR. These flows are also affected respectively by two factors that are not under the terminal's control: ship schedules (for the VS flow) and the arrival pattern of trucks at the terminal during the gate opening times (for the TR flow). Vessel schedules are known in advance by the terminal but may be subject to delays (as was often the case in the COVID-19 era); furthermore, depending on the size of the ship, the different number of containers to be unloaded at the terminal varies. Regarding the TR flow, if no truck appointment system is in place, trucks arrive at the terminal according to their needs. This is due to multiple factors, such as the constraints imposed by production processes, the opening times of the companies and inland terminals, the proximity of truck depots, etc. The overlapping phenomena and different speeds of these two cycles (external trucks and internal trailers), as well as the degree of saturation of the yard (i.e. its fill level), result in congestion at the terminal.

3 Case study of the PSA Genova Pra' container terminal

The proposed approach was applied to validate a case study of the PSA Genova Pra' container terminal, located in the Italian port of Genova. With a total throughput of approximately 1.46 million TEUs in 2022, PSA Genova Pra' is the largest container terminal in Italy and one of the leading container terminals in the Mediterranean area. It covers an area of 978,000 sqm with a capacity of 14,500 ground slots. 45% of the flows handled by the terminal are import flows, 80% of which are transferred by road. The terminal has a 1494-m quay, 12 truck gate lanes, and an 8-track rail park. It is also equipped with 12 quay cranes, 31 rubber-tyred gantry cranes (RTGs), 4 rail-mounted gantry cranes (RMGs), 25 reach stackers, and 90 trailers. The terminal has an Asian layout. Its yard is divided into 6 modules. Each module is approximately divided into 12 horizontal rows, apart from the depot areas designed with blocks (each 230 m long) perpendicular to the quay to minimize the impact of the wind blowing from the North. The blocks are dynamically assigned as import or export, depending on the needs imposed by daily volumes. The northern blocks are dedicated to import, while the southern blocks are dedicated to export. Recently, some of the import blocks have been converted to export. In addition to import, export, and depot, PSA Genova Pra' has 2 hazardous and 4 reefer blocks. In each lane of the yard blocks, a maximum number of 10 trucks can wait to be served by yard cranes at the same time (Fig. 2).

The terminal opens the truck pick-up phase when a ship has finished unloading. For large ships, it might be possible for the truck pick-up to be opened block by block as soon as the first-yard block has been completed to avoid a surge of trucks on completion of the vessel discharge operations. From then on, there is a peak in pick-ups so that more than 90% of the trucks arrive at the terminal within two days. The terminal handles more than 2400 trucks daily; each truck enters the terminal through a gate open 16 h a day. Figure 2 shows the number of truck arrivals at the container terminal on a typical day during the opening hours of the gate. There are mainly two peaks of external truck arrivals: early morning and mid-afternoon. What also emerges is how the peaks are immediately dampened, suggesting that the congestion phenomena studied here may be concentrated over short time horizons of approximately one to two hours.

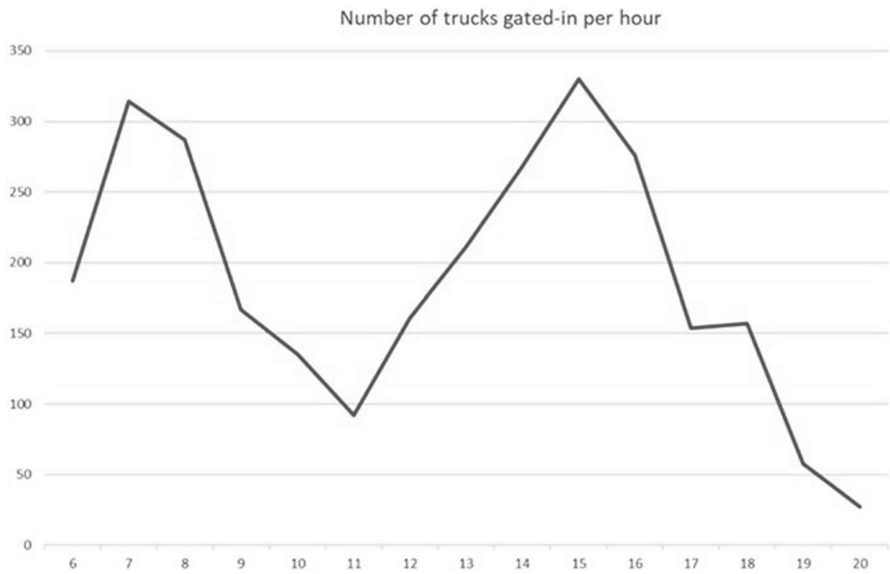

Fig. 2 Truck arrival pattern at PSA Genova Pra' container terminal on a typical day of activity

4 Methodology

Figure 3 describes the methodological framework adopted in this study. The input data of the traffic simulation model are traffic demand, derived from observations of terminal operativity and terminal conditions in terms of available equipment and possible disturbances (i.e. temporary closure of a yard block for scheduled maintenance of the road surface or yard cranes). The input parameters allow the definition of a certain number of scenarios to be tested in traffic simulation, suitably customized to faithfully represent the operativity of a particular container terminal and estimate its performance in various conditions. As principal output, a set of selected KPIs are evaluated to compare the terminal performance in alternative situations, also according to the implementation of potential control actions on terminal operations.

4.1 Micro-simulation model

The micro-simulation approach is based on a time-sliced approach widely used in traffic engineering studies. It can represent traffic interactions along connecting roads, vehicle queues, and vehicle energy consumption.

The layout and roads of a terminal are modelled considering vehicles of different types, in terms of their size and performance, to be tracked to reproduce interactions among vehicles.

Considering the limited resources available in terminals, internal traffic regulation is often organized on shared road sections, where truck congestion can occur with stop-and-start events. In these cases, tracking individual vehicles step by step provides a powerful tool to estimate congestion effects, emissions, and fuel consumption.

Based on the processes characterizing terminal operations, internal roads are modelled as sections, nodes, and roundabouts with specific lanes and traffic rules (Fig. 4). In particular, the import road cycle of the PSA Genova Pra' container

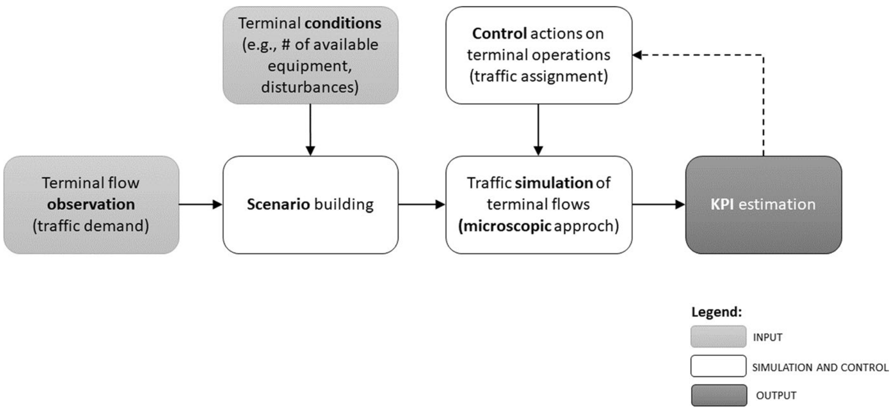

Fig. 3 Methodological framework

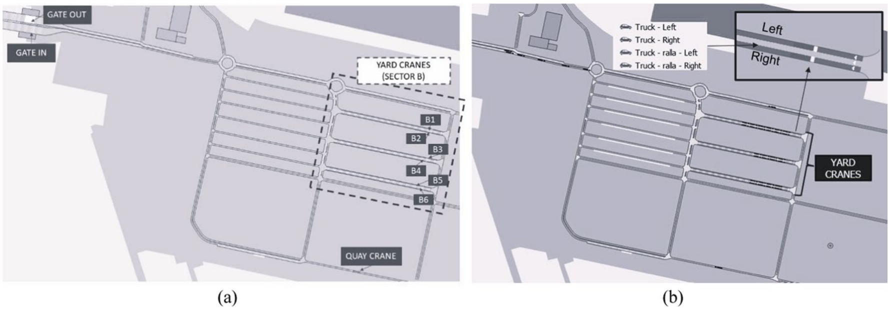

Fig. 4 Terminal layout in the micro-simulation model, detailing **a** the location of services and **b** lanes and vehicle classes ("ralla" means internal trailer)

terminal was modelled considering it is composed of VS and TR traffic flows, which interact with each other. The services at the terminal were simulated as shown in Fig. 4a.

The activities carried out by external trucks (TR) were simulated according to the following sequence:

- Arrival of trucks at gate-in;
- Container loading operations onto external trucks with yard cranes in yard blocks B1–B6; and
- Departure of trucks at gate-out.

The activities of internal trailers (VS), which is a cyclical process, were simulated according to the following sequence:

- Container loading operations by quay cranes from ships onto trailers and
- Container unloading operation by yard cranes from trailers into the yard in yard blocks B1–B6.

Figure 4b shows the modelling of sector B, where each road section includes 3 lanes: the central running lane and the extreme lanes for vehicles served by the yard cranes (B1 (left) and B2 (right)). To simulate the allocation of vehicles under yard cranes along either the right or left lane, vehicle types were classified into four classes: (1) left external trucks, (2) right external trucks, (3) left internal trailers, and (4) right internal trailers. This classification is required to assign vehicles to the two specific traffic flows and to realistically reproduce various vehicle loading and unloading operations under cranes (Fig. 4b).

TR and VS flows were modelled, emulating and adapting the operations of public transport lines with established routes and stops at specific points. However, TR and VS flows are simulated differently: external vehicles (TR) are modelled as vehicles that are continuously generated, similar to the method presented in Carboni and Deflorio (2017), (2020) whereas the flow generated by internal trailers (VS) is modelled as a predefined number of vehicles that carry out a certain number of activities in a loop. Linear public transport lines and circular public transport lines were used to model the behaviour of TR and VS, respectively (Fig. 5).

In the proposed model for marine terminals, each stop represents a vehicle's activity in the terminal at a specific location along the route in a certain amount of time, to comply an assigned task. In particular, public transport stops with specific waiting times were used to model the duration of activities performed by quay cranes and gate-out operations. Loading and unloading operations performed by yard cranes were instead simulated using simulation objects called metering, which are linked to detectors to identify vehicle types and apply different service times (waiting times at the metering) depending on the type of vehicle on arrival. The time needed by yard cranes to pick up operations on trailers is usually shorter than the time required for delivery operations on external trucks. Finally, the gate-in service was modelled with metering, which can delay the arrival of trucks to modify the incoming distributions of the six simulated public transport lines.

Traffic demand in the terminal was managed as is usually done in micro-simulation tools for the *Public Transport Plan,* combining in the plan the selected lines according to the scenario to be simulated. Two settings were adopted considering the two types of truck flows in our problem. The external trucks (TR) were modelled as a public transport line with interval departures set at 10 min to create a flow of 6 vehicles/h for each line. Instead, the internal trailers (VS) have a fixed departure time for each vehicle on each line following the cycling characteristics of the flow. Different public transport plans, composed of several public transport lines and timetables, were generated based on the simulative scenarios described in detail in the following sections.

Each micro-simulation experiment consists of ten replications for a one-hour simulation period, consistent with the duration of peak congestion detected in a port

Fig. 5 VS and TR flows at PSA Genova Pra' container terminal

terminal (Fig. 2). To avoid the empty network state at the initial simulation time, a warmup period equal to 30 min before the simulation period was used.

4.2 Input data: services time and traffic-flow allocations

Several exploratory scenarios were identified to test the model with specific input data, mainly concerning the traffic demand expressed in terms of incoming trucks from the gate-in and the duration required to carry out the activities involving trucks in terminal processes.

Table 1 shows the average data obtained from monitoring campaigns performed by the terminal operator on typical peak hours and used for setting all the service time operations in the model.

The import flows for a specific area of the terminal were simulated using three different traffic-flow assignments at the yard blocks, i.e. the three scenarios described in Table 2. The darker grey cells specify a service dedicated exclusively to unloading internal trailers (VS), average grey cells to external trucks (TR), and lighter grey cells are related to a mixed service.

The baseline scenario (S0) models the two traffic flows separately with no interaction in the sectors, meaning that four-yard cranes (B1, B2, B3, and B4) are allocated to ship unloading operations by the 5 internal trailers (VS), whereas the other yard cranes (B5 and B6) are assigned to container pick-up operations by the external trucks (TR). In scenario S0, yard crane B1 serves 2 of the 5 internal trailers, while the other 3 trailers are equally assigned to the remaining 3 cranes. The external truck traffic is equally distributed between yard cranes B5 and B6.

Scenario S1, called “Extreme”, reproduces a mixed management of the two traffic flows, in which yard cranes in blocks B1 and B2 can serve both trailers and trucks. Trucks can also use the other 4 blocks with an assigned flow of 20 veh/h to each block; the 5 internal trailers are assigned only to the first two blocks (2 trailers to block B1 and 3 to B2). In Scenario S1, the allocation of trucks is spread over all six available blocks and the arrival frequency of external trucks is increased (from 36 to 120 veh/h) to explore congested scenarios, leading to saturation of yard areas. In this case, saturation of yard blocks is reached in the simulation after one hour (Fig. 6), assuming a yard service time equal to 249 s (Table 1).

To stress the model further, a degraded scenario (S2) called “Partial Closure” was created to simulate the unavailability of a part of the yard area (i.e. with blocks B1

Table 1 Typical services time in the PSA Genova Pra’ container terminal

Service	Average (s)	Standard deviation (s)
Gate-in (TR)	24	4
Gate-out (TR)	19	7
Yard crane_loading (TR)	249	130
Yard crane_unloading (VS)	114	102
Quay crane_loading (VS)	136	59

Table 2 Traffic-flow allocation in yard blocks (VS = internal trailers; TR = external trucks)

ID	Scenario	B1	B2	B3	B4	B5	B6	Tot VS	Tot TR
S0	Base	VS (2veh)	VS (1veh)	VS (1veh)	VS (1veh)	TR (18 veh/h)	TR (18 veh/h)	5 veh	36 veh/h
S1	Extreme	VS (2veh) + TR (20 veh/h)	VS (3veh) + TR (20 veh/h)	TR (20 veh/h)	TR (20 veh/h)	TR (20 veh/h)	TR (20 veh/h)	5 veh	120 veh/h
S2	Partial closure	–	–	VS (2veh) + TR (12 veh/h)	VS (3veh) + TR (12 veh/h)	TR (6 veh/h)	TR (6 veh/h)	5 veh	36 veh/h

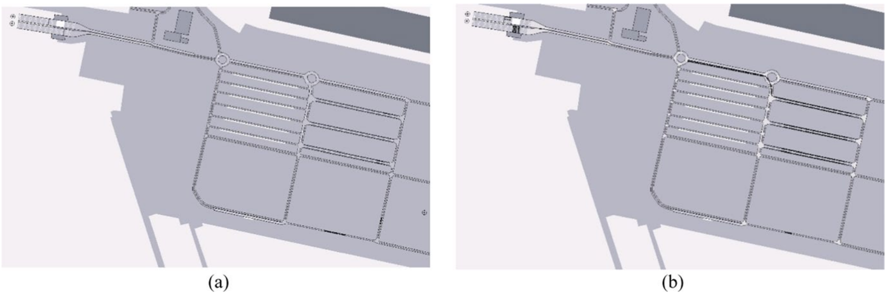

Fig. 6 **a** Scenario S0: far from saturation, **b** Scenario S1: saturation of yard blocks

and B2 disabled) and reallocating the entire flow to the remaining four blocks, again with a mixed approach. In this scenario, the new traffic allocation involves 2 internal trailers in block B3 and 3 trailers in block B4. The external truck traffic planned for blocks B1 and B2 is routed in blocks B3 and B4. This type of scenario should simulate the effects on terminal operations in case two blocks are not available for a certain period—such as for scheduled road pavement maintenance—handling the same traffic as the base scenario with only 4 operational blocks.

The S0, S1, and S2 scenarios were simulated either by using fixed average values of service times (deterministic cases: S0, S1, and S2) or by introducing a random distribution of approximately the same average values to consider stochastic phenomena and better represent the real-life operations of the container terminal (stochastic cases: S0_r, S1_r, and S2_r) (Table 2). The traffic-flow allocation at yard blocks is handled in the model through the composition of plans, including the selected lines that simulate the activity flows of external trucks and internal trailers in the six blocks (Table 2).

4.3 Output data: KPIs

The processes of a marine terminal (Sect. 2) considered within the scope of this study were measured and analysed by considering a set of KPIs (Table 3), considering the principal stakeholders, i.e. terminal operator, truck drivers, and the local

Table 3 Selected KPIs for each stakeholder and related model outputs

Stakeholder	KPI	Micro-simulation model output	Unit
Terminal operator	Yard/quay crane utilization rate	Occupancy (detector)	%
	Queue length at yard/queue crane	Max queue (detector)	veh
Truck drivers	Turnaround time	Total travel time (public transport line)	min
	Delay	Delay time for external trucks (system)	sec/km
Social community	GHG emissions	Total CO_2 emission (system)	g
	Pollutant emissions	Total NOx emission (system)	g

community. Road congestion inside a terminal primarily impacts the efficiency of terminal operations and its environmental performance. KPIs related to a terminal operator's point of view are the utilization rate (occupancy of a specific detector placed at the "crane service") of yard and quay cranes and the length of queues for loading and unloading operations. A crane utilization rate of 100 per cent means that the crane is always fed by vehicles waiting for loading and unloading operations. Therefore, for the terminal to be efficient, this value should always be approximately 100 per cent during the peak hour, indicating that there is no idle time for the crane (either in the yard or on the quay). Although the typical use of yard cranes over the whole day is generally lower (approx. 60–70%), in case of observations during "peak hours", when the crane is always busy, 100% as the target level can be accepted.

The truck turnaround time, i.e. the total time between the gate-in and gate-out of a truck in a terminal, is one of the most important KPIs for external drivers. Other important performance indicators are the waiting time at the yard cranes and fuel consumption. Finally, the negative impacts of traffic congestion at terminals on the community concern air pollution and greenhouse gas emissions. For this purpose, the microscopic traffic simulation tools can be extended, including the instantaneous emission model, which can be directly connected to step-by-step traffic data. In Int Panis et al. (2006), used in our experiments, the emissions considered are nitrogen oxides (NOx), volatile organic compounds (VOC), particulate matter (PM), and carbon dioxide (CO_2). These emissions are calculated according to vehicle type, its instantaneous speed, and acceleration. To derive the emission functions for heavy vehicles, more than 6000 measurements were taken in Int Panis et al. (2006) on two types of heavy-duty vehicles: Iveco Eurocargo and Volvo FH12-420.

5 Results

The KPIs identified and described in the previous section were evaluated based on the average values obtained from 10 replications for each micro-simulation experiment for the six scenarios. Figure 7 shows the number of external trucks inside the simulated terminal (coloured bars in the graph) as the difference among vehicles entering and leaving the terminal gate during the selected intervals. Scenario S1, i.e. the scenario with an intensification in external traffic (Table 2), clearly displays an increase in the difference between the two cumulative plots of vehicles during the simulation due to the congestion in the block, as also confirmed by other KPIs in the following graphs. In contrast, the average number of external trucks remaining inside the terminal is more constant in the S0 and S2 scenarios, which have a comparable flow of incoming vehicles (Fig. 8). For the selected simulation period, Fig. 9 shows the number of external trucks inside the terminal for all the stochastic scenarios considered.

The introduced randomness makes possible the damping of "abnormal" peaks, due to determinism, and better reproduces the variability, allowing an improved representation of the real variability, typical to terminal operations. For example, the

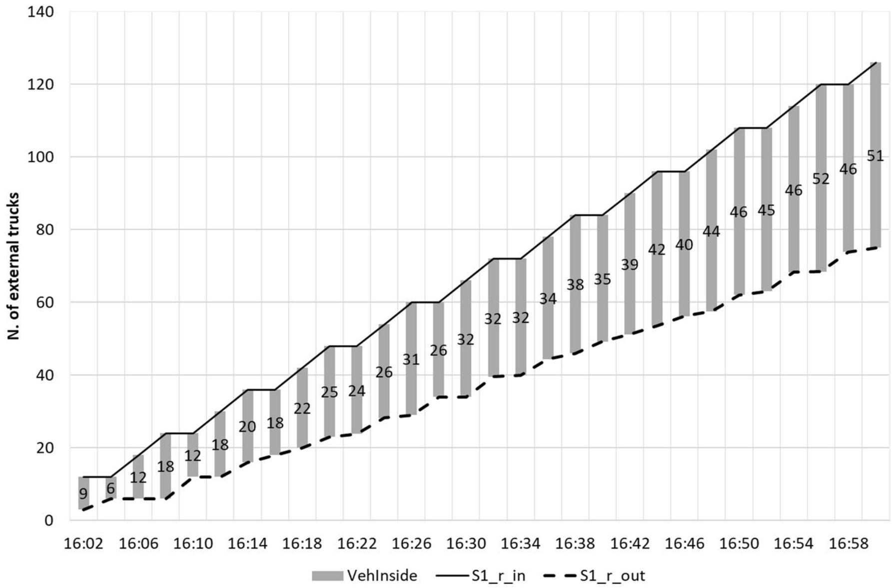

Fig. 7 Cumulative plots of arrivals and departures for external trucks during simulation in scenario S1_r

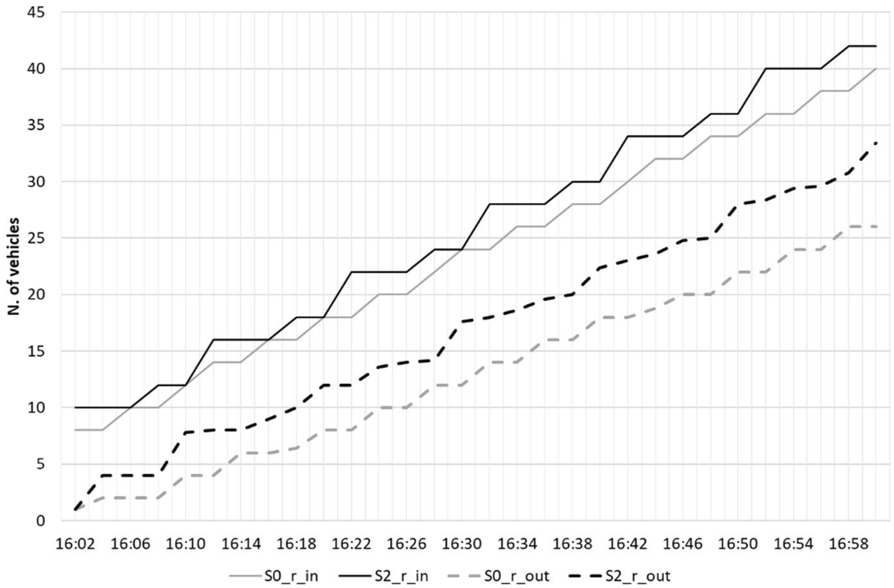

Fig. 8 Cumulative arrivals and departures for external trucks during simulation in scenario S0_r and s2_r

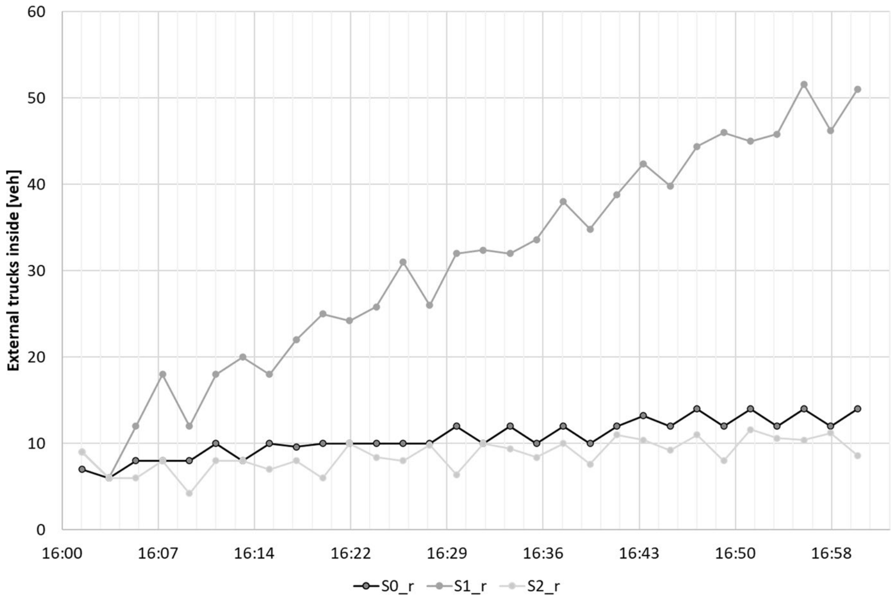

Fig. 9 Number of external trucks inside the terminal during the simulation period

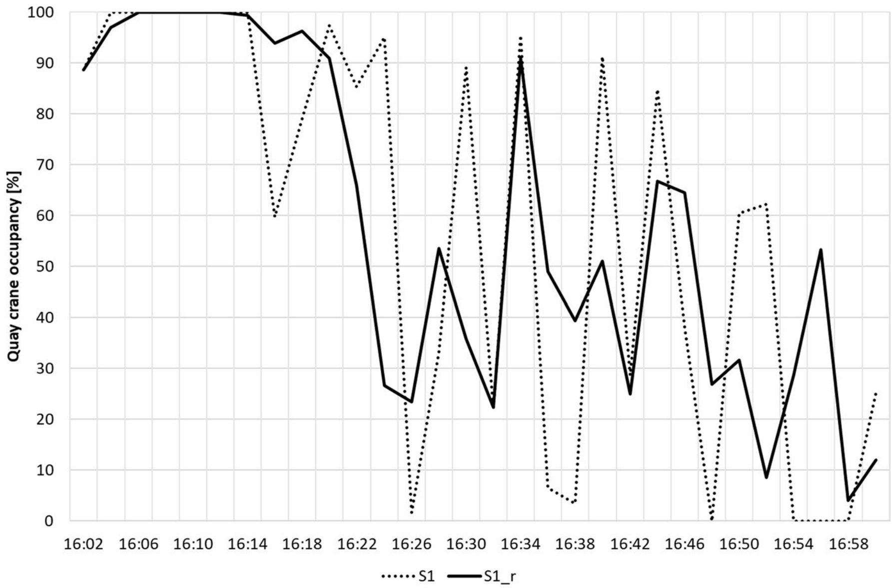

Fig. 10 Quay crane occupancy in deterministic (S1) and random (S1_r) scenarios

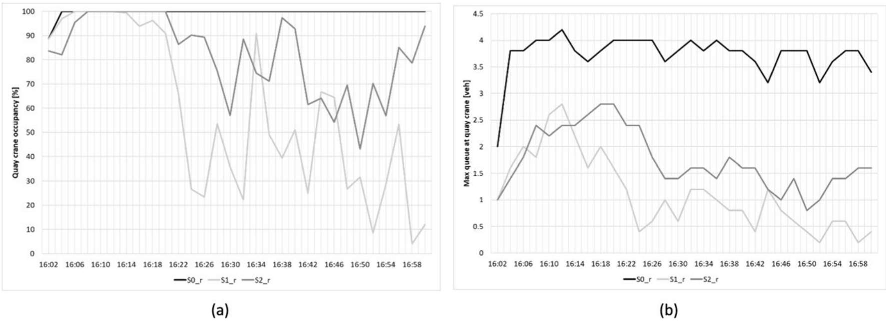

Fig. 11 **a** Quay crane occupancy and **b** Max number of trailers in the queue at the quay crane in scenarios S0_r, S1_r, and S2_r

effect of randomness on quay crane productivity in the extreme scenario S1 is shown in Fig. 10.

Figure 11a shows the quay crane occupancy for the three scenarios with randomness. In the base scenario S0_r, the quay crane is always fed by 4 internal trailers which retrieve containers, bringing them to the yard blocks. In the S1_r and S2_r scenarios, congestion in the yard increases the waiting time for the trailers to unload containers in the yard blocks. This requires a longer time for the trailers to complete their cycle and return to the quay crane to retrieve more containers for unloading.

Figure 11b shows the maximum number of trailers in the queue at the quay crane for the simulation interval. In the S0_r scenario, this number is always approximately 4, meaning that the trailers finish the "quayside-to-yard crane" cycle quickly and can keep the quay crane supplied without making it wait. In the S1_r and S2_r scenarios, on the other hand, the average number of trailers queueing at the quay crane sometimes becomes zero. In this case, trailers are queuing at the yard crane, as shown in Fig. 12. In fact, the occupancy level of the yard crane in block B1 displays that in scenario S1_r, this yard crane is never idle, meaning that there is always a trailer or an external truck waiting to be served. Conversely, in the base scenario S0_r, in which the B1 yard crane only has to unload containers carried by trailers, the average occupancy rate is less than 50%, indicating time frames when the yard crane is inoperative. This value can be read in conjunction with the occupancy of the quay crane, which is always operational and fed in the base scenario.

The external truck delay indicator, expressed in sec/km, clearly shows that the most congested scenario is the future scenario (S1_r), where the arrival rate of external trucks increases (Fig. 13). The increase in external truck flow was also explored in scenario (S2_r) with four operating blocks, but the sector reached saturation after a few minutes of simulation, and it was excluded. The S2_r scenario of traffic concentration on only 4 blocks evidently brings an increase in the average delay of external trucks intermediate between the base scenario (S0_r) and the scenario with extreme traffic (S1_r).

The total travel time of external trucks inside the terminal represents the turnaround time, i.e. the time required to carry out delivery operations (in the proposed case study) from gate-in to gate-out. Figure 14 reports the turnaround time,

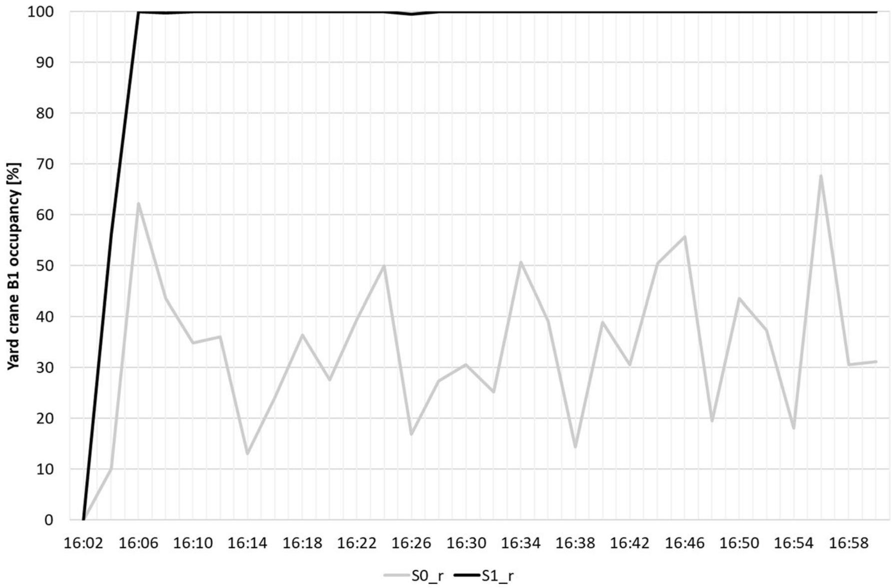

Fig. 12 Yard crane B1 occupancy in S0_r and S1_r scenarios

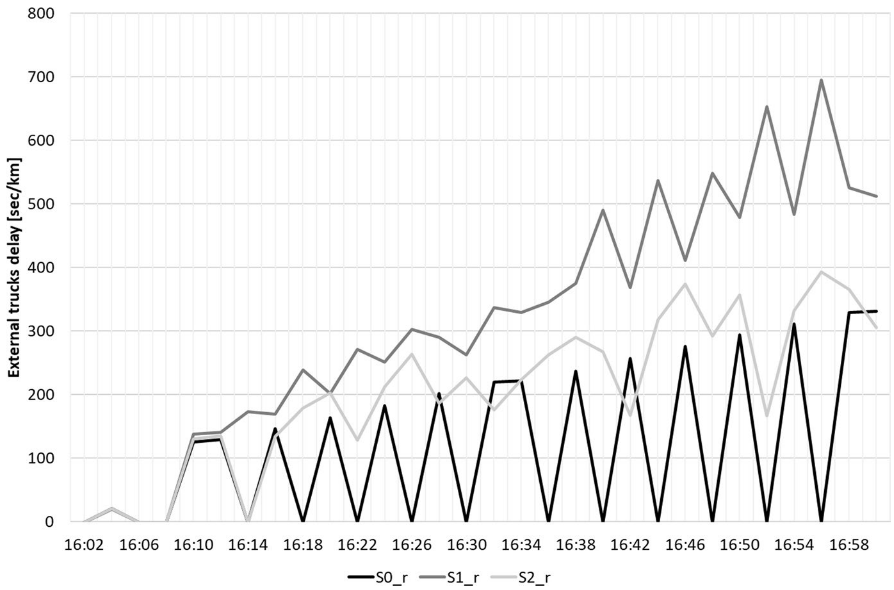

Fig. 13 Delay time for external trucks in scenarios S0_r, S1_r, and S2_r

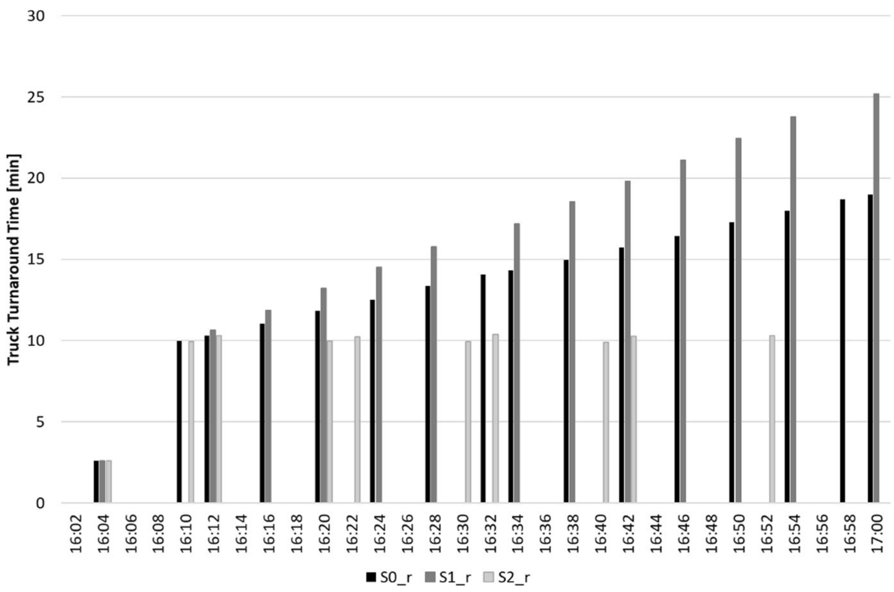

Fig. 14 Truck turnaround time for external trucks of one specific lane for scenarios S0_r, S1_r, and S2_r

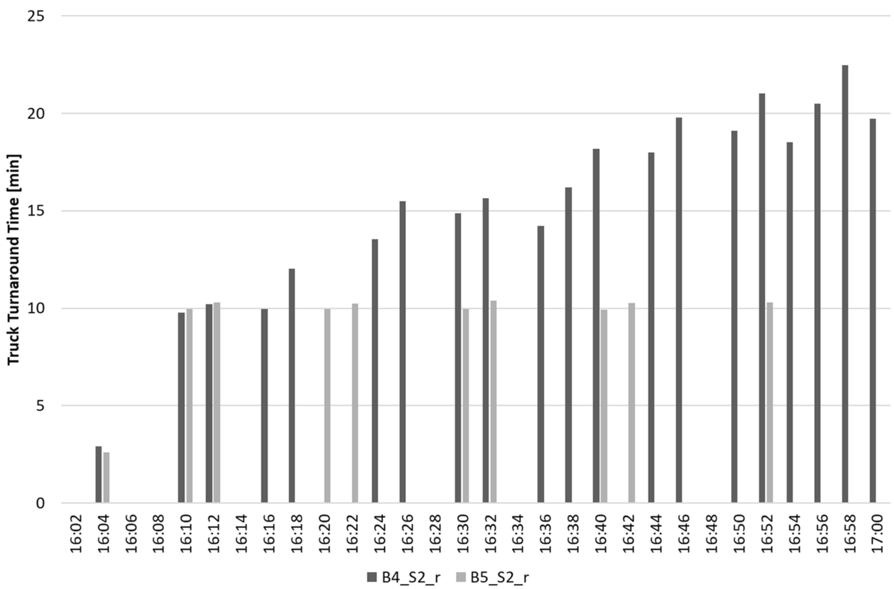

Fig. 15 Turnaround time for external trucks served in yard areas B4 and B5 in S2_r scenario

expressed in minutes, for external trucks served in the same yard block (B5), to compare how this value differs in the three scenarios. As expected, the highest value is recorded in the most congested scenario: S1_r.

Figure 15 shows the turnaround time for external trucks travelling to two different yard areas in the same scenario (S2_r): B5, which is dedicated only to external trucks, and B4, which serves both external trucks and internal trailers (in both cases the frequency of truck arrival is the same). As can be expected, turnaround times for external trucks increase if the yard area serves both vehicle types (trailers and trucks). This example shows how this performance indicator can be used to investigate the effects of different yard block management strategies.

Finally, road congestion leads to an increase in CO_2 emissions, which contribute to climate change, and in pollutant emissions such as NOx typical of heavy goods vehicles, which affect local air quality (Fig. 16). The S1_r scenario causes the greatest environmental impact, being the most congested scenario.

6 Discussion

Modelling of road traffic flows inside container terminals was performed using a microscopic traffic simulation tool in which vehicles are tracked step-by-step along their routes according to the specific sequence of operations for loading and unloading at various locations. Discrete-event simulation is not able to reproduce traffic dynamics in a logistics node with the same accuracy. Moreover, the method presented in this study is flexible, modular, and replicable; it can be applied to any container terminal, modifying the layout, service times, type of vehicles, etc.

The software generates statistics and indicators that allow one to describe a terminal's performance from different perspectives (operational, environmental, etc.) and from the point of view of different stakeholders.

A traffic micro-simulation model that has already been extensively calibrated and validated in a commercial software makes it possible to accurately replicate the dynamics of vehicle traffic and exploit the use of reliable and accurate emission models.

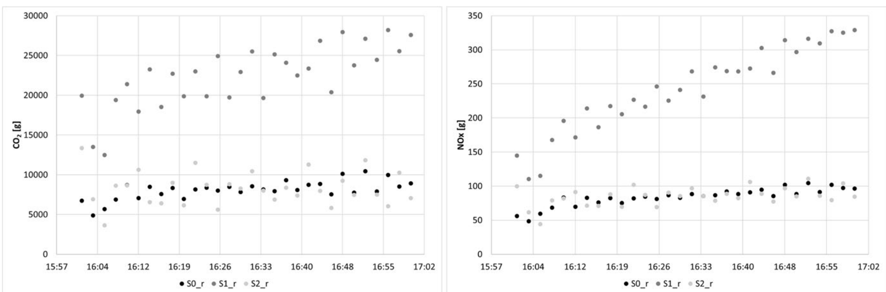

Fig. 16 Total CO_2 (left) and NOx (right) emissions for scenarios S0_r, S1_r, and S2_r

Traffic simulation tools are commonly and widely adopted to describe road transport systems and various types of vehicles. The challenge of the proposed approach was to adapt the elements available in a tool to the framework of a port terminal. To sum up, the main challenges for the micro-simulation model were the following:

- Fixed number of trailers with cyclic tasks. A specific type of public transportation was used to reproduce them with a circular line between two stops, simulating the loading/unloading service of quay and yard cranes with vehicle departures at fixed times.
- Different service time at yard cranes for external trucks and internal trailers. This was handled with metering that changed the duration of the phase (that considers the vehicle waiting time) based on the type of vehicle recognized by the detector.
- Multiple service point locations at yard blocks to be managed by yard cranes. Virtual metering devices with specific and different logic were implemented in the left and right lanes to reproduce two-yard cranes for each roadway. Then, four categories of vehicles were introduced to implement these strategies: right internal truck, left internal truck, right external truck, and left external truck.
- A set of truck lanes shared by trailers and external trucks served by a couple of yard cranes. As with the previous challenge, this is solved by metering to represent the yard cranes described in the previous point.
- Limited space for parked trucks in each yard block and the movements of trucks when two cranes are working close together. The layout reproduction and the dimensions of the assumed vehicles allow the terminal spaces to be realistically replicated. Moreover, in the model, the trucks stay in the queue on the lane identified in the specific block.

7 Conclusions

This paper presents a methodology, using microscopic traffic simulation, to model and simulate the vehicular traffic dynamics of the import container cycle in a container terminal. Terminal management strategies are varied, and disturbance events are considered. The final aim is to assess congestion phenomena and environmental impacts.

Several KPIs were calculated and evaluated from the viewpoints of different stakeholders: terminal operators, trucking companies, and society.

The proposed approach was successfully applied to the PSA Genova Pra’ container terminal, located in the Italian port of Genova, considering a portion of the yard area where trucks pick up import containers. The processes of the terminal that were simulated are characterized by shared resources. Six scenarios were chosen to test the model and the identified challenges, by changing block management strategies, increasing external truck traffic, and simulating a possible temporary partial closure of the terminal yard. Some scenarios used deterministic values for the times of the simulated operations, while in others, randomness was introduced to obtain results closer to reality and less extreme trends.

The results obtained show that the traffic micro-simulation could be applied to a typical marine terminal context by adapting the simulation elements to the features of the container terminal considered and the challenges it presents. The proposed approach makes it possible to assess terminal congestion issues by exploring different scenarios through the comparison of suitable performance indicators that the traffic micro-simulation software offers as output. The operations of objects such as cranes or ships are represented as simplified processes according to their service times and, therefore, are not simulated as detailed objects, as occurs in discrete-event simulation, which is typically adopted to simulate container terminal operations. Unlike classical approaches to simulate container terminals, the perspective of this paper is that of haulage companies, which are important stakeholders and customers for terminal operators.

Future research will be devoted to modelling and simulating the export road cycle integrated with the import road cycle and implementing new operating logic for cranes working in the yard and on the quay.

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