Port Efficiency for Connected Vehicles and Digital Infrastructures

Subjects: Transportation Science & Technology

Contributor: Orlando Marco Belcore , Massimo Di Gangi , Antonio Polimeni

In logistics and freight distribution, scheduling and cost efficiency are two crucial issues for transportation companies that look with favour at the innovation introduced by Intelligent Transportation Systems (ITS). This research contributes to the research by: (i) proposing a generic framework for the integration of autonomous and connected vehicles with physical infrastructures; (ii) evaluating the opportunity to manage traffic arrivals according to vehicles' priority and testing the effects of the introduction of a buffer zone outside the maritime port; (iii) improving efficiency and security within the terminal area by reducing waiting time and avoiding interference between flows. Moreover, the proposal for a discrete-event simulation model to assess terminal capacity in a ro-ro terminal is presented.

Digital Infrastructures | Port Efficiency | connected vehicles | smart port

1. Introduction

Since the spread of the e-market, consumers' behaviours have widely changed, thus influencing traffic freight flows [1][2][3]. Concerning freight logistics, a declared objective of the European Community regards the transfer of 30% of road and combined road–rail freight to short sea shipping [4]. In 2021 in Italy [6], ro-ro terminals accounted for 6,299,321 units (trucks and semi-trailers), with an increase of 23% compared to 2020 (5,113,112 units) and 11% compared to 2019 (5,618,282 units); in this sense the integration between physical and digital infrastructure as well as the management system of the port results of interest in optimizing freight distribution.

Ordinary disruptions may be caused by interfering operations, traffic conditions or other events. Deviation from the fixed scheduling causes consumer dissatisfaction and affects infrastructure efficiency. Moreover, truck companies are susceptible to delays, and this sensitivity increases when fleets and cargoes have to deal with perishable products. Transportation companies look favourably to innovation introduced by automated vehicle fleets and coordination and control introduced by connectivity [7]. In accordance with the Society of Automobile Engineers (SAE) standards, SAE J3016 [10], the automated vehicles classification includes five levels. In the smart road domain, the intention is to develop a dedicated short-range communication system (DSCR) for the full implementation of digitization through communication protocols, such as Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I), thus improving traffic safety, convenience and energy efficiency [11][12]. Communication among vehicles vouches for awareness, platooning strategy for trailer trucks, heavy goods vehicles, and cooperative manoeuvres. On the other hand, communication with infrastructure enables information, instructions and negotiation [13]. The best departure time, optimal route, flow regulation, optimal speed and density can be managed, also delivering information on the best time to recharge in accordance with the timetable and log way trips [14]. Thus, in general, connected vehicles (automated and connected) have the potential to increase infrastructure capacity and harmonize traffic conditions.

2. History

The necessity to move to full automation in freight logistics is higher than in passengers to limit the power force and costs and achieve better performance on time and numbers of deliveries. In the future, automation will represent the standard among all carriers [7]. Consequently, autonomous commercial vehicles such as trucks are expected to be available before autonomous cars for individuals; therefore, autonomous driving in the maritime terminal is expected to materialize soon [15]. Nevertheless, this expectation could be delayed, and approximation may suffer from different degrees of market penetration. Till today, close to a mind-off transition period, concepts of integrating autonomous freight vehicles into traffic systems require separated traffic lines, free route choice or fixed paths in mixed traffic conditions [16].

The context of maritime terminals has interested many researchers who focused on several approaches to test and increase performance at the terminal. The approaches vary for the analytical method and the degree of granularity, however, discrete-event simulation (DES), in general, has always represented a popular approach among researchers [17], and many studies focus on its application in solving phenomena related to the management of maritime terminals. In the field of ro-ro terminals (albeit in a much smaller way), discrete-event simulation has been of interest to a wider audience of researchers who dealt with the management of landside and seaside arrivals; to optimize scheduling and allocations problems so long as in a ro-ro terminal, trailer trucks and vehicles cannot usually be stacked for limited spaces and due to the nature of the trips and freight on board. Preston et al. [18] by means of DES, tested the residual capacity in the e-roll-on-roll-off ferry port located in Dover (UK). The simulation approach was used to organize what-if scenarios under the hypothesis of ordinary disruptions and increasing demand. As KPI, the author utilized both queue time at the gate and pollutant emissions. Iannone et al. [19] assessed the impact of managerial decisions about loading, unloading and storage allocation. They conducted a discrete-event simulation assessing for each alternative the economic impact of each alternative and pollutant emissions. Kaceli [20] used simulation in the contest of a ro-ro terminal to predict planning scenarios and determine the necessary infrastructural needs. Even more, as stated by Ozkan et al. [21], ro-ro terminal operations specifically needed a focus on timetable coordination and scheduling, thus integrating different levels of communication. As a consequence of this, at least three variables of interest resulted: the number of trucks arriving at terminals, the distance between terminals and Ro-Ro ship capacity. Abourraja et al. [22][23] discussed the problem of flexibility in decision-making in the context of a ro-ro terminal. In it, they proposed a generic framework to be used as a tool for specific decision support models at the terminal. The assessing method was addressed utilizing different KPIs, such as workload, time and distance. Park et al. [24] proposed an automated solution with the use of Automatic Guided Vehicles (AVG) for a ro-ro terminal. The model analyzed the economic benefits of introducing AVGs, thus assessing the achieved level of productivity. Varying the number of available AVGs, the queue time was used as KPI to optimize the number of vehicles and average waiting time. Muravev et al. [25] mainly focused on DES as an operative tool to test the effectiveness of the proposed solution. They modelled the operation for a ro-ro terminal using two different software packages (Arena and AnyLogic) and considered model scalability.

On the other hand, container ports, in general, have always represented the most interesting field of application due to the higher level of transport demand and daily operation. In this sense, truck control arrivals and the management of yard slot allocations were widely debated among academics. For example, Jovanocic [29] designed a TAS in the context of two container ports (Los Angels and Seattle (USA). A scheduling problem is defined in it, and the corresponding integer programming model is developed from the truck driver's perspective to increase user satisfaction. Similarly, Azab et al. [30] developed a TAS to achieve a higher level of workload. The proposed algorithm evaluated the best truck arrivals schedule to minimize the total costs of both the terminal and the trucking companies. Performances were tested by measuring truck turnaround time and length of queues. Srisurin et al. [33] simulated daily activities within the terminal area to assess terminal capacity in terms of handling, allocation and where house options. Performance was tested under six scenarios whose nature varies from tactical measures to planning policies and solutions. A further detail of granularity was of interest to Schoroer et al. [34], who developed an Inter Terminal Transport system in the terminal of Rotterdam accounting for different solutions and machines. Both priority and first-in-first-out (FIFO) strategies were tested during the simulation, and mean delay per ride was used as KPI to test the effectiveness of the configuration.

Infrastructural planning and terminal capacity are crucial topics, and several researchers focused on productivity. Rusca et al. [35] utilized discrete-event simulation for investigating performance in a container port through berthing capacity and for operative planning of logistic processes under different arrivals flows. Carteni and De Luca [36] addressed port container performance through simulation of the handling activities. Results validation was carried out for short- and long-term planning horizons by evaluating local and global performance indicators.The DES was used to model the environment and subsystem characteristics, operations and performance indicators (for the land-side equipment, contractual agreements, associated penalties, and berthing policies). Triska et al. [40] also dealt with port capacity assessment. The simulation was carried out with the Monte Carlo technique and tested in a DES model. The authors studied economic and operational criteria for the port capacity (berths, storage slots and truck gates). The gate performance and the optimum number of the server were at the basis of the works developed by Guan and Liu [41][42]. The paper applied a multi-server queuing model to analyze marine terminal gate congestion and an optimization model was developed to balance gate operation costs and truckers' waiting time. The introduction for a truck appointment system resulted as the best option to introduce.

An agent-based approach at the basis of the planning and capacity of the system for both Assumma and Vitetta [43] who simulated loading and unloading operations and Fleming et al. [44] who focused on pooled queue strategies.

Table 1 synthetically reports main feature of the previous work concerning performance and simulation methods for both ro-ro and container terminals.

Table 1. Classification of the literature review (source: by the authors).

Paper	Terminal	Simulation Approach	Software	Model Scope
Preston et al.	ro-ro	DES	not stated	Planning; Capacity
Iannone et al.	ro-ro	DES	ARENA	Planning Areas
Kaceli	ro-ro	DES	ARENA	Gate; Yard Capacity
Muravev et al.	ro-ro	DES	ARENA; AnyLogic	Scehduling; Capacity
Ozkan et al.	ro-ro	DES	not stated	Sched.; Coordination
Abourraja et al.	ro-ro	DES	not stated	Bert; Yard Capacity
Park et al.	ro-ro	DES	not stated	AVGs Introduction
Sharif et al.	ro-ro	Agent-Based	NetLogo	Capacity; Info
van Vianen et al.	Multi-Modal	DES	not stated	Stackers operations
Parola and Sciomachen	Multi Modal	DES	Witness	Coord. Modal Shift
Jovanocic	Container	DES	not stated	Truck Arrivals System
Azab et al.	Container	DES	FlexSim CT	TAS; Congestion
Neagoe et al.	Container	DES	Python	TAS; Handling
Nadi et al.	Container	DES	not stated	TSMS
Srisurin et al.	Container	DES	SIMIO	Slot Allocation; Hand.
Schoroer et al.	Container	DES	Delphi	Internal Transport
Rusca et al.	Container	DES	ARENA	Planning; Capacity
Carteni and De Luca	Container	DES	Witness	Planning; Capacity
Cimpeanu et al.	Container	DES	Witness	Planning; Berth Occ.
Li et al.	Container	DES	not stated	Bert; Yard Capacity
Alvarez et al.	Container	DES	C ++	Bert; Yard Capacity
Triska et al.	Container	Monte Carlo	MatLab	Bert; Gate; Storage
Guan and Liu	Container	Queue Theory	not stated	Gate Capacity; Servers

Paper	Terminal	Simulation Approach	Software	Model Scope
Assumma and Vitetta	Container	Agent-based	ARENA	Planning
Fleming et al.	Container	Agent-based	NetLogo	Planning; Capacity
Chen et al.	Container	Genetic Algorithm	not stated	TAS
Ambrosino and Peirano	Container	Linear Optimization	C#	TAS
Mihn et al.	Container	Genetic Algorithm	not stated	TAS
Minh and Huynh	Container	Genetic Algorithm	not stated	Congestion
Yang et al.	Container	[50][51] Queue Theory	not stated	Slot Allocation; Waterway

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- the transport companies send their daily plan to the terminal operator, pointing out the nature of the freight (dangerous, perishable, general merchandise, ...); they have to confirm the number of trucks, the platoon scheme, the desired shipping company and the naval service to board on;
- vehicles receive routing information from smart road devices installed in the corridors and the terminal cloud system through a communication protocol, the same reports about traffic conditions around the infrastructure, queue estimation in the buffer area, vessel approaching and final direction;
- the planned route, the next vessel berthing and available space are stored in the system; moreover, to avoid long waiting, the system coordinates approaching and manoeuvres as well corridors assignment;
- the terminal area is provided with a stable cloud monitoring system equipped with roadside units and an optimization traffic control system that enables communication highlighting yard occupation (of the buffer area) and the number of vehicles waiting for the embankment.

As a primary step towards this integration, this paper focuses on developing an operational framework to manage arrivals in the terminal whose primary aim is to improve the efficiency of landside operation to reduce waiting time in the system.

3. Application

A discrete-event simulation lets the analyst simulate what-if scenarios under different traffic conditions to test the efficiency of tactical solutions and prevent congestion phenomena affecting the terminal. **Figure 1** represents the synthetic scheme of operations for a vehicle arriving at the terminal. The flow diagram depicts the main steps into the system, such as registration and priority class assignment, and subsequently go through different paths before leaving the terminal area.

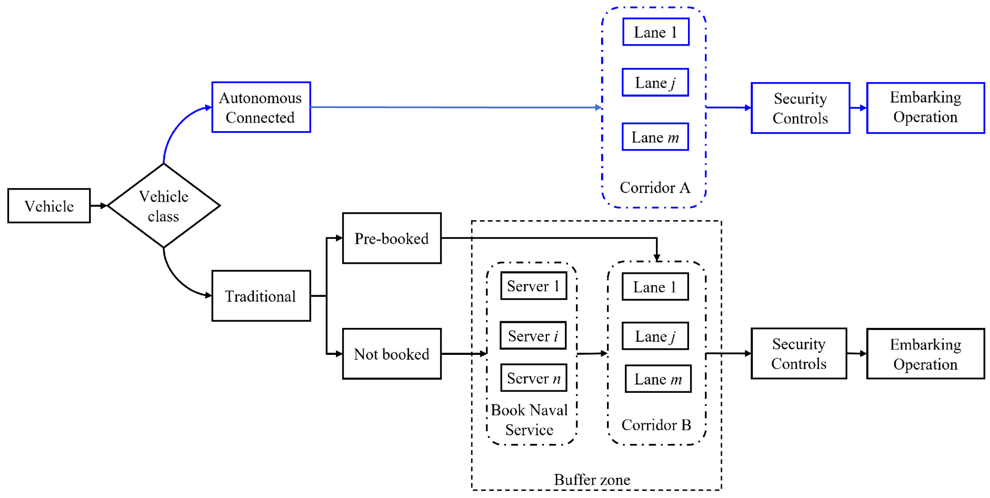

Figure 1. Simplified scheme of the Port of Tremestieri (source: by the authors).

A generic *vehicle* approaching the port passes through an approach corridor equipped with automatic number plate recognition (ANPR) sensors. Therefore, the system matches in the archive if the incoming vehicle has already confirmed its presence and, in the affirmative case, classifies it as *autonomous/connected*; otherwise, it is identified as a *traditional* vehicle. The former proceeds to the inner area of the terminal (in an established *lane* of the *corridor A* following variable message) and, according to *security controls*, it continues up to the internal buffer area ready for the *embarking operation*. Inside the *buffer zone*, traditional vehicles were further differentiated in *pre-booked* and *not booked*. The first subgroup directly reaches the first available slot in the queuing *lanes* in the *corridor B*. Non-booked vehicles have to choose (according to FIFO regulation) a *server* for ticket operation, reserving their slot in the first available vessel. Once the ticket operation is completed, they reach the proper lane, waiting to be called in the inner area of the terminal for *embarking operation* (after eventual *security controls*). Once vehicles are organized in groups, they receive information on the next step and path to the embarking area.

The key performance indicators chosen in our simulation foresee, for different vehicles class, the average time needed to be ready for the embarking operation. Further analysis on the average waiting time in the system (for vehicle class) also lets us know the average number of arrivals served on the first available vessel.

4. Progress

The general framework described in this paper, exploiting the discrete-event simulation, contributed to the research by focusing on the importance of efficiency in critical infrastructure such as a maritime terminal and highlights the importance of digitization for physical infrastructure, thus representing a valid tool in supporting the decision process. In more detail in this paper, a case study on managing landside operations at the maritime terminal of Messina-Tremestieri has been illustrated to demonstrate how the proposed modelling framework can simulate daily traffic conditions, taking into account the effects of the introduction of automated/connected vehicles.

Its main scope was to evaluate the possibility of improving port efficiency using regulation strategies and new planning solutions, thus reducing the cyclical queue phenomena observed during on-field analyses. The highlighted benefits reside in the reduction of the total in-time system.

The simulation was run multiple times to test the system's capability to deal with variable traffic conditions over the 8 hours of the peak period. The discrete-event approach allowed the simulation of vehicles' arrivals in the terminal area and addressed incoming flows by organizing priorities. The framework included a buffer zone to be used as a basin for traditional vehicles to prevent overcrowding of the yard area. Concerning the automated vehicles, the proposed procedure assigns them a dedicated corridor and a high priority. Furthermore, the simulated regulation will enable the terminal operator to serve an additional surplus of traffic. Introducing the pre-booking system for autonomous vehicles helps manage access at the terminal, taking into account the residual capacity to embark on vessels. Regulation strategy based on priority class and reservation to specific naval services resulted in an adequate solution for embarking vehicles on the first available vessel, thus reducing waiting time in the terminal area. Introducing a buffer zone outside the terminal helpfully reduced long queues in the inner areas.

Thus, it achieved a twofold objective. First, in line with the intervention proposal planned by the public administration, the proposed scenario assessed the effect of introducing an external buffer zone and a new regulation for the operations within the terminal area. The achieved performances were tested by using as key performance indicators the total time in the system and the embarking factor on vessels, thus highlighting the possibility of reducing the ordinary disruption and low performance at the maritime barrier that, as stated, represents a crucial node for the area's economy. Finally, the further value of this study resides in the field of sustainability for both users and logistics operators who could benefit from more precise regulation and certainty of operations at the terminal, thus avoiding long waiting. The implementation of the proposed framework contributes to the field of sustainable transportation (as recognized by United Nations in proposing the goal number 11, a sustainable transport system plays a primary role in the sustainable development) providing a decision support system to mitigate effects due to queues (reducing pollutant emissions and noise) and to increase efficiency of maritime transport by optimizing the load level of the vessels.

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