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Article

Masterplanning at the Port of Dover: The Use of Discrete-Event Simulation in Managing Road Traffic

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Abstract: The Port of Dover is Europe's busiest ferry port, handling £119 billion or 17% of the UK's annual trade in goods. The Port is constrained geographically to a small area and faces multiple challenges, both short- and long-term, with managing the flow of five million vehicles per year to/from mainland Europe. This article describes some of the work that the Port is doing to minimize the impact of port road traffic on the local community and environment using discrete-event simulation modeling. Modeling is particularly valuable in identifying where future bottlenecks are likely to form within the Port due to projected growth in freight traffic and comparing the effectiveness of different interventions to cope with growth. One of our key findings is that space which can be used flexibly is far more valuable than dedicated space. This is supported by the much greater reduction in traffic congestion that is expected to be achieved given a 10% increase in freight traffic by reallocating space at the front of the system to temporarily hold vehicles waiting to pass through border control and check-in compared to extending the amount of space for ferry embarkation at the rear of the system. The importance of flexible space has implications for port design that can be applied more broadly. Modeling is also useful in identifying critical thresholds for vehicle processing times that would cause the system to become overwhelmed. Increasing the check-in time by just three to five minutes, for example, would completely exceed the Port's capacity and produce indefinite queueing. This finding has important implications for Brexit planning. From a wider context, the research presented here nicely illustrates how simulation can be used to instill more evidence-based thinking into port masterplanning and support "green port" and other corporate sustainability initiatives.

Keywords: port masterplanning; corporate sustainability; traffic flow modeling; discrete-event simulation

1. Introduction

Port masterplanning is the process by which ports determine and communicate their medium- to long-term strategic plans. Masterplanning is vital for linking a port's strategy to over-arching local and regional transport strategies and ensuring that a port meets its commercial, social, and environmental objectives [1]. Integration of "green port" policies aimed at reducing emissions of air pollutants and greenhouse gasses from logistic operations, in particular, is increasingly being seen as a core element of port masterplanning [2–4]. In this regard, port masterplanning is linked intrinsically to the three pillars of corporate sustainability (i.e., balancing economic growth with environmental and social considerations) [5,6].

A general challenge associated with masterplanning is that port infrastructure is often complex, expensive and long-lived. At the same time, decisions to build or repurpose infrastructure is often

made with limited knowledge of future business trends, technology, and environmental regulations. From this perspective, port masterplanning is best viewed as a process of complex decision-making under uncertainty. To help address this, techniques from the field of operations research (OR) are becoming ever more popular for structuring and supporting the development of port masterplans. Simulation modeling is especially well suited for addressing problems at all levels of planning, including operational, tactical, and strategic, for which uncertainty and time are key features [7]. Indeed, the World Association for Waterborne Transport Infrastructure (PIANC) advocates the use of simulation across a range of port functions, such as vessel maneuvering, tide and sedimentation analysis, and traffic flow prediction [8]. Note that a number of different simulation approaches can be adopted (e.g., system dynamics, discrete-event, agent-based, and mixed), with each method having its strengths and weaknesses. Selection of a particular method to use depends in part on the type of problem being modeled, the granularity of available data, and the degree of abstraction needed to address questions of interest.

A number of timely reviews have appeared in the literature recently presenting overviews of the application of OR methods in port and maritime planning [9–15]. A particularly good review of how simulation models are applied in ports and container terminals is presented by Dragović et al. [14], who trace the evolution of methods used and the breadth of problem areas addressed since the 1960s. Of the 219 articles evaluated by Dragović et al., the majority focus on container stack loading and unloading, which is discussed in more depth in a study by Lehnfeld and Knust [15]. Another notable finding is the sheer variety of simulation techniques and software used, with discrete-event simulation being the most common type of framework (e.g., [16]) but with agent-based models also frequently employed (e.g., [17]). An entire section of the review is devoted to port traffic, specifically marine vessels. Examples mentioned include modeling ferry traffic of Aegean ports given seasonally varying demand [18], modeling safety and vessel interactions in San Francisco Bay [19], and detailed modeling of ferry maneuvers at the Port of Dover [20]. The Dragović et al. review concludes that simulation modeling is a pre-requisite of effective port development planning due to the degree of complexity of port systems [14].

For modeling vehicle traffic within ports, agent-based simulation tends to be the methodology of choice. For example, causes and possible solutions to traffic congestion at the Port of Chennai are analyzed by Rajamanickam and Ramadurai [21] using the agent-based microsimulation environment PTV Vissim. The authors of this study find vehicle document processing to be a limiting step in the system and propose both technological and structural solutions to mitigate congestion. Similarly, Demirci [22] developed a whole-port simulation model to identify processing bottlenecks and possible investments to improve cargo handling, warehousing, and transport operations at Trabzon Port in Turkey. The simulation explicitly models both shipping vessels and cargo loading/unloading vehicles (e.g., trucks and forklifts). In addition to more land-side focused modeling studies, other whole-port modeling tools are described in the literature, including Portsim, a discrete-event model developed primarily for military logistics planning [23] and a general hybrid discrete-event and agent-based framework for modeling cargo facilities implemented in AnyLogic and Java [24].

The focus of the current study is the Port of Dover in the UK. The Port of Dover is Europe's busiest ferry port, handling upwards of £119 billion or 17% of the UK's annual trade in goods along a 180 km trade expressway [25]. As a roll-on-roll-off (aka ro-ro) ferry port, the Port of Dover faces multiple challenges with managing the flow of over 10,000 vehicles per day to/from mainland Europe. Ferry operations are situated on the Port's Eastern Docks, which are constrained geographically to a small area bounded by cliffs to the north, the sea to the east and south, and the town of Dover and major road links to the west (Figure 1). What is more, the Port operates in a highly dynamic environment. This includes both short-term operational stressors (e.g., delayed ferry movements caused by storms, variable staffing levels, labor strikes, and heightened security in response to acts or threats of terrorism) and long-term strategic stressors (e.g., projected growth of freight traffic and the possibility of additional border and customs checks on vehicles following Brexit). With little recourse

to increase its existing footprint, it is vital that the Port finds smarter ways of doing things if it is to maintain and grow the ferry business.



Figure 1. Aerial view of the Port of Dover Eastern Docks (Source: [26]). The black dashed line roughly marks out the physical boundary of the Eastern Docks.

In an effort to instill more evidence-based thinking into its masterplanning exercise, the Port of Dover has over the past few years invested in the development of simulation and other OR methodologies to inform operational policies and capital investment decisions. This article describes some of the work that the Port is doing to minimize the impact of port road traffic on the local community and environment using a whole-port discrete-event simulation model to improve traffic flow forecasting and identify the best use of space to reduce traffic congestion.

Road traffic at the Port of Dover has previously been the subject of various simulation studies. Roadknight and colleagues report findings of two studies involving application of the microscopic traffic flow simulation software Vissim [27,28]. A key advantage of traffic flow simulators is the high level of detail that can be ascribed to individual driver behavior and choices. For example, using Vissim, Roadknight et al. were able to simulate how traffic divides over a set of parallel weigh-bridges by defining simple rules of thumb for driver behavior rather than assigning weigh-bridge choice probabilistically [27]. However, as the authors point out, difficulties can arise when simulating large systems made up of many interdependent entities due to high data requirements and the likelihood that small errors in model design can result in highly inaccurate outputs.

Given the stochastic nature of the system, simulation provides a valuable tool to address both the short-term operational needs of the Port of Dover as well as investigate long-term strategic choices. Where agent-based and discrete-event models have been explicitly compared, agent-based models are typically judged as being more accurate [29]. For the current study, however, discrete-event simulation was adopted given the flexibility it offers in terms of quickly reconfiguring the model to analyze different possible future scenarios and its reliance on a minimal set of assumptions about the Port's physical layout and the movement of traffic.

The Port system has some interesting features from a queuing theory perspective. Queuing theory mainly focuses on stable queues in which arrival rates are less than service rates, resulting in stable and predictable behavior over time. In contrast, the Port of Dover has arrival rates that are non-stationary but vary systematically within each day. Since the Port operates efficiently overall, these arrival rates

can transiently exceed processing rates, resulting in queues which move rhythmically from sub- to super-saturated and back. As pointed out by Newell [30], queue behavior where arrival rates and service rates are closely matched is particularly chaotic and therefore harder to predict.

In what follows, we describe the construction and validation of a discrete-event simulation model of the Port of Dover and its application in both short-term and long-term planning. Key findings of our study are intended to yield general insights that can be used to guide sustainability initiatives and infrastructure decisions at other ports. As a bit of context, modeling originally began in late 2015 with the goal of identifying potential bottlenecks in the system driven by anticipated growth in freight traffic and the development of possible interventions to reduce queuing traffic. The model has subsequently been adapted to explore possible implications for the Port regarding the UK's decision in 2016 to leave the European Union (i.e., Brexit) and support post Brexit planning. The full ramifications of Brexit are currently unknown. However, modeling provides a convenient means for carrying out "what-if" analysis in the absence of reliable information on future traffic volumes or required changes to vehicle processing.

The work presented here is noteworthy in several respects. First, our study stands out within the literature by focusing on road traffic in a ro-ro ferry port rather than the usual container port. Second, whereas simulation is most often used to help streamline existing operations, an additional primary aim of our investigation is to examine how simulation can support strategic, long-term planning and investment tied to port masterplanning. Finally, as part of our analysis, we address sustainability issues by considering a key performance indicator (i.e., Dover Traffic Assessment Project (TAP), discussed below) that relates to the impact of traffic queues on the local community and the environment.

2. Materials and Methods

2.1. Study Area

The Port of Dover is a large roll-on-roll-off ferry port located in Dover, southeast England that provides one of the two main modes of transport (along with Eurotunnel) for road vehicles traveling between the UK and mainland Europe. The Port handles three main vehicle types: large freight vehicles (or lorries), passenger cars/motorcycles, and coaches, which drive onto ferries under their own power and drive off at their destination. Currently, there are two ferry operators at the Port of Dover, P&O Ferries and DFDS Seaways, which run cross-channel services to Calais and Dunkirk in France. Up to 5 million vehicles travel through the Port annually.

The Port system is moderately complex, with multiple traffic types, arrival rates which have within-day, weekly, and seasonal variations, and a series of manned check points, each of which is preceded by space for queuing traffic (Figure 2). The Port is best thought of as a "system of systems" [31], in which the overall behavior of the system emerges from the interactions among its component processes and queues.

There are two main entrances to the Port: the A20, which approaches the Port along the coast from Folkestone to the west, and the A2, which approaches the Port inland from Canterbury to the northeast. The majority of freight vehicles and coaches arrive from the A20. The A2 has a mixture of traffic but is made up mainly of passenger cars. After arriving at the Port, vehicles are required to pass French border control, better known as Police aux Frontières (PAF), and other security checks before making their way to check-in booths to collect boarding passes for their designated ferry service. Vehicles wait for ferries in the assembly area next to the docks. The final stage of journey through the Port is ferry embarkation or "uplift" (i.e., removal of vehicles from the system) when a ferry enters the Port, docks, unloads incoming vehicles, loads outgoing vehicles, and then departs.

Immediately inside the port entrance is a highly flexible space called the "buffer zone" for temporarily holding vehicles waiting to pass through PAF and/or check-in. The buffer zone has the capacity for 220 lorries or around 600 passenger cars/motorcycles. Traffic is directed at the port entrance using electronic signs above individual lanes within the buffer zone so subsets of vehicles (either type

of vehicle or those booked on a particular ferry service) can be selectively held in the buffer zone or allowed to bypass it directly to PAF.

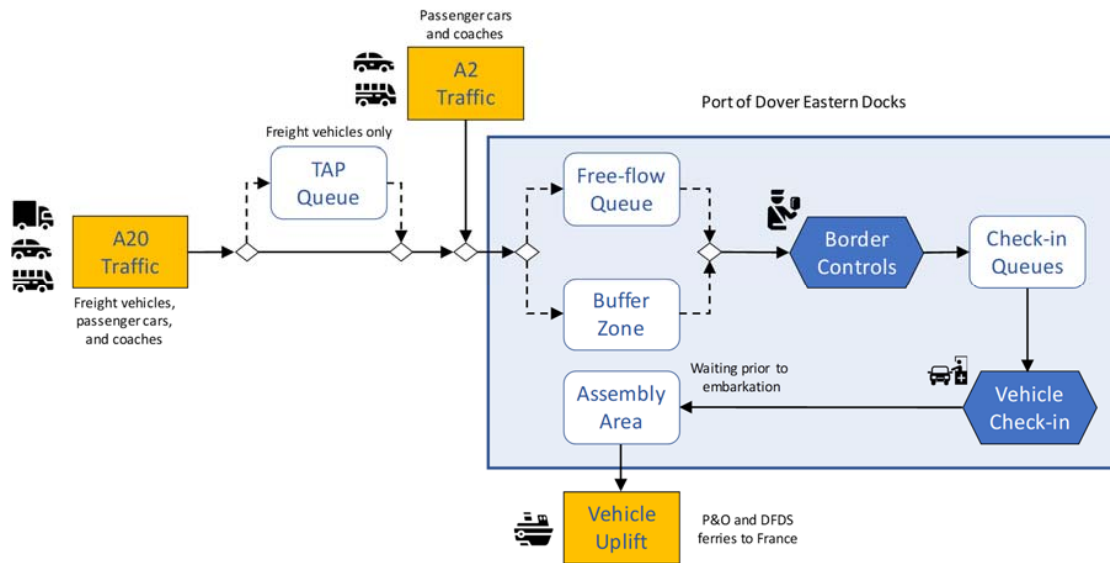


Figure 2. Simplified schematic of the Port of Dover Eastern Docks. Figure adapted from [32]. TAP = Traffic Assessment Project.

Under extreme conditions, such as prolonged periods of bad weather or labor strikes, the M20 motorway, which freight and other vehicles travel along prior to joining the A20, is sometimes closed to traffic and used as a giant lorry park. Operation Stack, as it is commonly known, is rare. In 2015, there were 31 days of Operation Stack, but none from 2016 to 2019. It is estimated that Operation Stack cost the UK economy £250 million per day [33]. In 2019, Operation Stack was replaced by Operation Brock, which introduced a contraflow system to buffer freight traffic on the M20. At the start of 2020, however, permanent barriers used to operate the contraflow system have started to be removed.

In April 2015, Highways England implemented a local traffic management system, known as the Dover Traffic Assessment Project (TAP), to control freight traffic approaching the Port along the A20. The main purpose of TAP is to reduce congestion of Dover's local road network and improve air quality within the town and avoid the necessity of triggering Operation Stack/Brock. TAP, which is composed of a series of traffic lights to regulate flow along the left lane of the A20, is only put into operation when needed due to heavy congestion within the Port. Passenger cars/motorcycles and coaches are not held in the TAP queue, so they get preferential access to the Port when TAP is in place.

2.2. Model Development and Validation

A discrete-event simulation model of the Port of Dover Eastern Docks was developed using the Simul8 software package. The model considers only outbound traffic (i.e., traffic traveling from the UK to France) as outbound flow is effectively independent and does not compete for resources or space. The reason for this is that under the Le Touquet agreement, UK and French border controls are juxtaposed, with French controls located in the UK and UK controls located in France. Consequently, there are relatively few checks on inbound traffic and little or no queuing. Figure 3 shows an annotated flow diagram of the simulation model. The various components of the model are described in Table 1. Main input data to the model include the following.

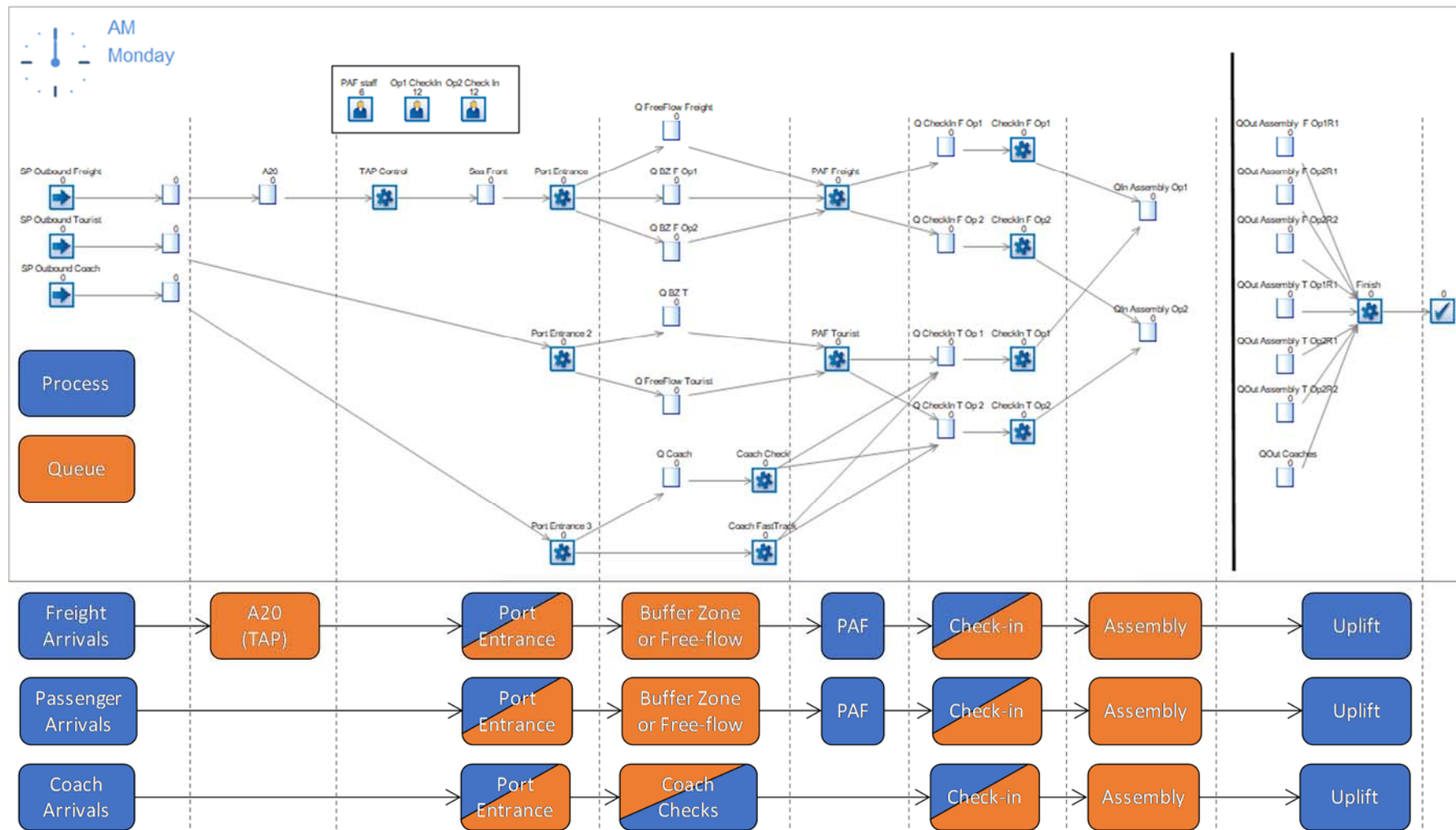


Figure 3. An annotated flow-chart of the Simul8 simulation model. Figure adapted from [32]. PAF = Police aux Frontières.

Table 1. Main components of the simulation model.

	Component	Description
Transient Entities	Ferries	Ferry vessels differentiated by ferry operator (P&O and DFDS), destination (Calais and Dunkirk) and uplift capacity.
	Road Vehicles	Road vehicles differentiated by vehicle type (freight vehicle, passenger car/motorcycle, coach), intended ferry operator and destination.
Resident Entities	PAF	French border control (aka PAF) and other security checks.
	Coach Checks	Separate border control and other security checks for coaches.
	Check-in Booths	Check-in booths specific to ferry operator. Can be reallocated to different traffic types dynamically depending on demand.
Queues	Ferry Uplift	Ferry uplift is specific to ferry vessel and destination.
	TAP	Queuing freight traffic on the A20 due to TAP.
	Buffer Zone	Area for temporarily holding vehicles waiting to pass through PAF.
	Free-flow Queue	Queue for free-flowing traffic approaching PAF.
	Coach Queue	Queue for coaches waiting for border control and other security checks.
	Check-in Queue	Queue for vehicles in front of check-in booths.
	Assembly Area	Marshalling area for vehicles waiting to board ferries. Segregated by ferry operator.

- The capacity of each queue or holding area in the model is measured in freight equivalent units (FEUs), with 1 FEU equal to 18 m of road space (including free space in front and behind a vehicle). Coaches are estimated as 1 FEU, while passenger cars and motorcycles are specified as 1/3 of an FEU (6 m of road space).
- Parametric distributions for process times were fit to data collected from both manual samples (stopwatch estimates) and automatic loggers where available (e.g., logs of check-in booth gate raises). Distributions were derived using Stat::Fit software and the best fitting distributions chosen based on *p*-values of the Kolmogorov–Smirnov test.
- Half-hourly arrival rates for each traffic type are based on historical patterns.
- Ferry schedules and vessel capacities are based on schedules currently in use as well as analysis of historical schedules and vehicles carried.

In reality, ferries take tens of minutes to load and unload. In the simulation, however, embarkation is modeled as an instantaneous event at the time of ferry departure. Vehicles chosen for embarkation is based on a first-come-first-serve basis according to time of check-in, a protocol that more or less matches current practice.

The primary key performance indicator (KPI) chosen for the simulation study was the predicted number of TAPs per week. This is a convenient proxy for days on which the Port's capacity to handle inbound traffic is exceeded for whatever reason. TAP events have significant implications for Port staff, since TAP and buffer zone queues must be actively monitored and traffic systematically conveyed from TAP to the buffer zone. In addition, Port police are needed to provide traffic control at the front of the TAP queue. TAP is also well-known to local and national agencies. Finally, TAP is a vital metric from a sustainability perspective, since it is both a social measure of inconvenience to local stakeholders (i.e., congestion of local roads near the A20) and an indirect environmental measure since it involves stop-start queuing freight traffic that could otherwise be at rest with engines switched off. We therefore assume that TAP reduction is one of the main enablers for the Port to meet its social and environmental objectives.

Secondary KPIs monitored in the simulation were: (i) total time in system starting from entering the extended Port system (approximately 6.3 miles from the entrance to the Port) and ending at

embarkation; (ii) use of the buffer zone, which provides an indicator that the system is near or at capacity; and (iii) emissions of CO₂ (a primary greenhouse gas) and NO_x (a regulated air pollutant) produced by freight vehicles in the TAP queue. Estimates for CO₂ and NO_x are derived by calculating the average speed for each freight vehicle in the TAP queue and then applying the UK Department for Transport speed–emissions curves [34]. As a conservative approach, we used parameter values for 34–40 metric ton articulated heavy goods vehicles (HGVs) fitted with diesel engines meeting the Euro VI emission standard. This class of HGVs corresponds to the most common type of articulated freight in 2020 and the most fuel efficient [35].

Verification and validation of the model was performed using Sargent’s schema as a guide [36]. Verification consisted of a line-by-line check of the model code and systematic checks and documentation of each entity in the simulation to ensure they behaved as intended. “White-box” testing was conducted by varying simulation inputs and confirming the simulation responded appropriately (e.g., increasing daily volumes of traffic to observe progressive saturation of queues and monotonic increases in traffic queuing outside the Port). Verification tests were run independently by two of the authors (G.C.P. and J.O’H.), one of whom did not work on model implementation (J.O’H.). Face validity was confirmed by demonstrating the working simulation to Port operational staff, who confirmed the correct sequence of operations and that no key features were absent.

Additional operational validation work was carried out to ensure the simulation model was suitable for decision support purposes. First, outputs of the simulation model were compared with a simple, deterministic system dynamics model developed in-house by the Port for estimating total traffic in the system (i.e., traffic that has entered the system, expressed in FEUs, but not yet embarked). The system dynamics model (implemented in Excel) is designed to represent the Port only at a very high level. It combines vehicle arrival patterns with ferry arrival/departure schedules to identify periods during which waiting traffic is likely to be held within the Port and the amount of traffic held. Despite its very different underlying methodology, the discrete-event simulation model is able to reproduce outputs very similar to the system dynamics model (Figure 4), but has the added advantage (given its much greater level of detail) of showing where queues are located in the Port, which traffic types are queuing for which ferry services, and when TAP events are likely to occur.

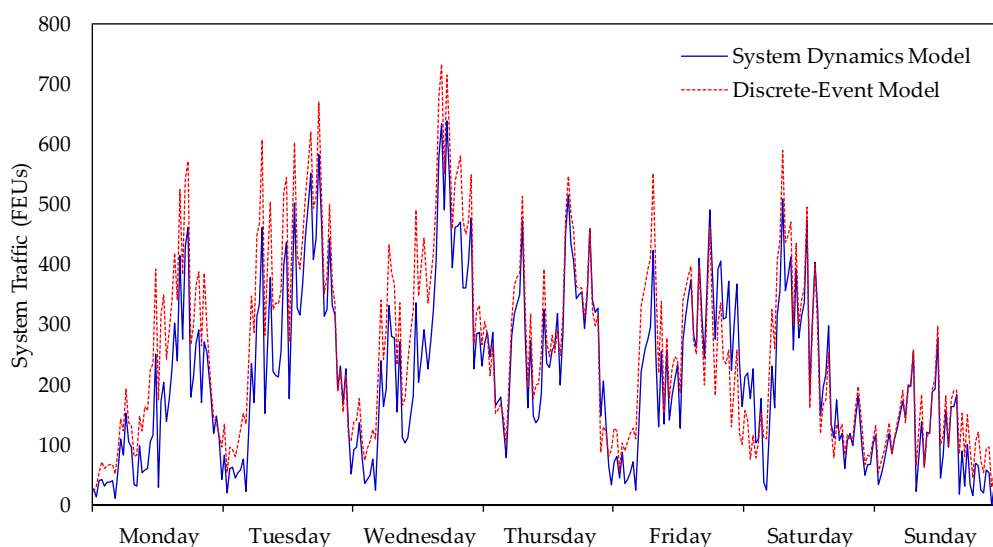


Figure 4. Comparison of number of vehicles in the Port system, measured in freight equivalent units (FEUs), for the systems dynamics model and the discrete-event simulation model given inputs for a typical week. The Pearson correlation coefficient for the two time series displayed is 0.94.

Second, the simulation model was compared against real-time traffic monitoring data collected by the Port. One of these systems includes Blip Systems BlipTrack sensors, which monitor traffic flows by

sensing mobile phone and Global Positioning System (GPS) signals. A typical freight week from April 2016 was used as a benchmark by comparing simulated transit times against sampled BlipTrack dwell times and cumulative ferry uplift. Additionally, weeks with known vessel refits, check-in computer system failures, or slow processing at PAF were used to check that the model was sensitive to observed stressors. Figure 5 shows the results of such an event, in which a late-afternoon reduction in the number of available check-ins triggers first use of the buffer zone, then an extended period of TAP, which eventually clears by mid-evening. Comparison of simulated dwell times with sampled BlipTrack dwell times on the A20 for the day in question shows that the model correctly identifies the start and end of TAP and closely approximates maximum dwell time in each half-hour period and the overall pattern of rise and fall of dwell times. Note that BlipTrack segregates traffic into fast and slow streams, so free-flowing traffic is not recorded. The stretch of road takes about 8–9 min to cover, hence a value of 8.6 min is shown for BlipTrack outside the TAP event (i.e., 15:30–17:00 and 21:00–22:30).

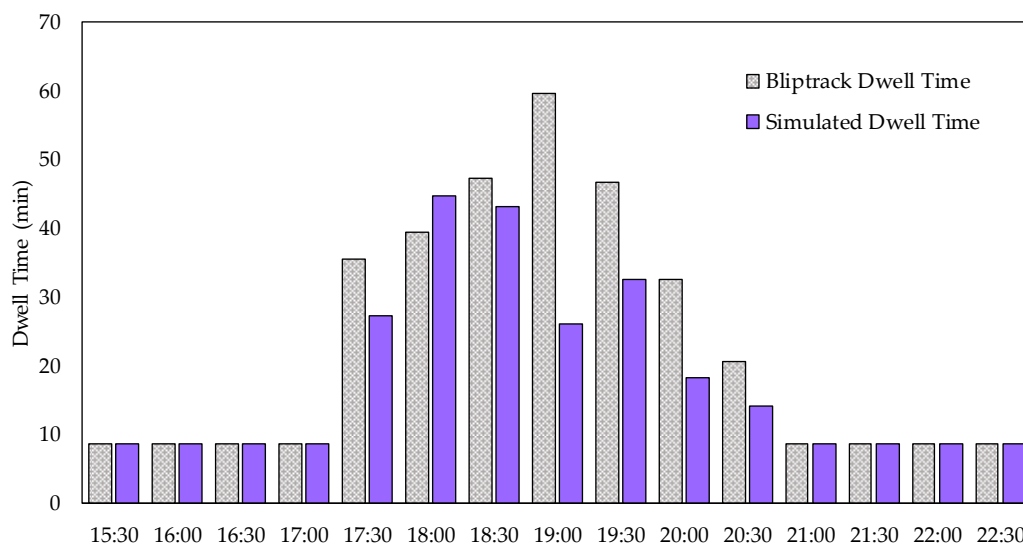


Figure 5. Comparison of simulated dwell times in the TAP queue with observed dwell times from BlipTrack during a TAP event on the evening of 2 February 2016.

The simulation model can be run over two basic time intervals. A one-week version of the model is quick to run and modify, affords a greater number of trials, which improves the precision of statistical analyses, and gives outputs comparable with the system dynamics model. Results reported in this paper are based on a one-week runtime. Alternatively, the model can be run over a full year (actually 48 weeks as the first two and last two weeks of the year must be excluded, since they are atypical and distort year-to-year comparisons). A one-year run is slow to execute and not ideal for conducting multiple trials but has the advantage in that it provides an estimate of the number of TAP days per year, which is better for communicating results to external stakeholders.

3. Results

3.1. Anticipated Impact of Freight Traffic Growth

At the time the Port of Dover's last masterplanning cycle was initiated, the volume of freight traffic was steadily increasing over time. In just the two-year period 2013–2015, freight grew by 30% [25], bringing concerns about environmental sustainability and the feasibility of maintaining business growth of this level to the fore.

The first set of simulation experiments were designed to assess the capacity of the Port system to cope with increased freight traffic. As baseline for comparison, the week of 18 April 2016 was chosen to represent a moderately heavy freight week. This was the Port's fifth busiest week for freight

that year but typical in the sense that no extraordinary events or weather conditions prevailed, and within-week and within-day arrival patterns were not out of the ordinary. Since the focus of our analysis is on infrastructure planning rather than driver behavior, the ferry schedule was set to the highest frequency of sailings seen in 2016, while staffing at both PAF border controls and check-in booths was set to the number of service channels available (rather than constrained by actual staffing). Traffic flow was simulated for this baseline scenario and then again for a 10% growth in freight vehicles by simply multiplying the instantaneous arrival rates for freight traffic by 1.1. This was considered a sensible choice given trends in freight traffic growth in preceding years. Tourist and coach traffic were left unchanged.

Figure 6 shows a single one-week run of the simulation for both the baseline and 10% freight growth scenarios. At baseline, a typical high-freight week with no unusual circumstances is easily handled by the Port. Traffic has a mid-week peak of around 900 FEUs and some use of the buffer zone on Wednesdays but no instances of TAP. In contrast, with a 10% growth of freight, queuing traffic peaks to over 1100 mid-week, with three activations of the buffer zone and two instances of TAP.

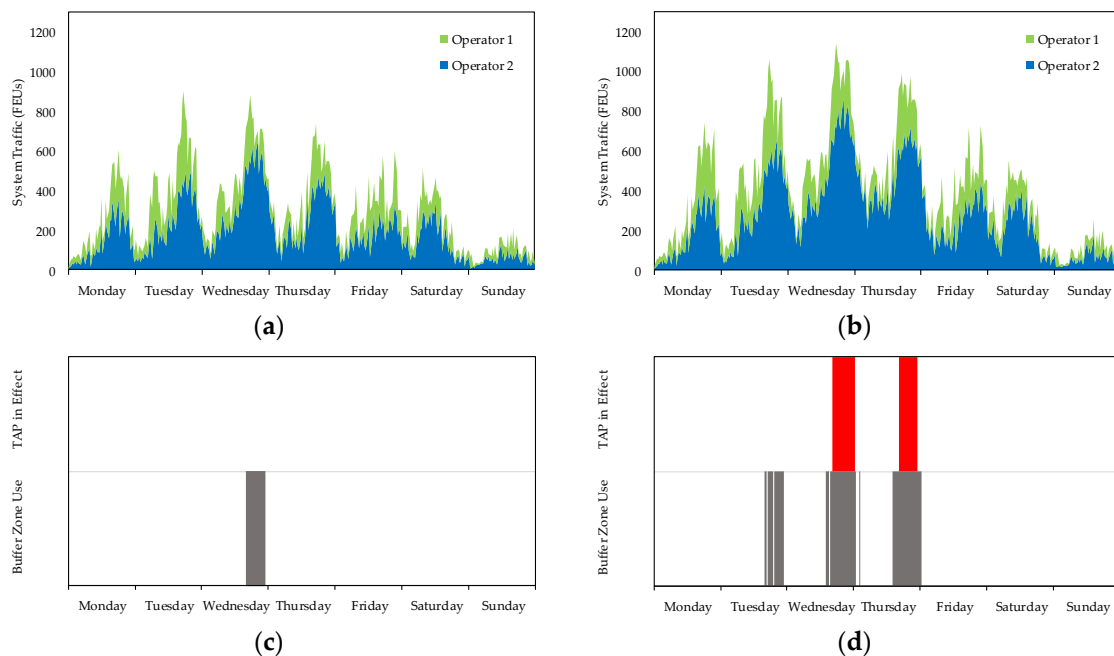


Figure 6. (a) Simulated Port traffic by ferry operator (blue and green) over a typical week under baseline conditions and (b) following a 10% increase in freight traffic, along with (c) buffer zone (grey) and TAP use (red) under baseline conditions and (d) following a 10% increase in freight traffic.

Summary results comparing the base case and 10% freight growth scenarios given 100 simulation runs are provided in Table 2. These results tell a similar story to Figure 6. Given 10% freight growth, vehicles remain in the system an average of 25% longer, rising from 89 to 111 min. More importantly, the number of weekly TAPs increases significantly, going from near zero to 1.6 per week, while CO₂ and NO_x emissions rise by 12%. The consequence is that there are periods when 223 freight vehicles are queuing in TAP, equating to approximately 2.5 miles of queuing traffic, as well as an excess of 5.4 kt of CO₂ and an excess of 3.5 kg of NO_x emitted per week. Note that excess emissions represent the levels of emissions over and above what is expected following a 10% increase in vehicle numbers and is expressed simply as projected CO₂ and NO_x emissions minus 1.1 times baseline CO₂ and NO_x emissions.

Table 2. Traffic flow metrics for the base case and 10% growth in freight traffic scenarios. Values reported are means over 100 simulation runs along with 95% confidence interval half-widths.

Scenario	Buffer Zone				TAP Queue ¹			
	Time in System (min)	Max Size (FEUs)	Max Dwell (min)	No. TAPs (per wk)	Max Size (FEUs)	Max Dwell (min)	CO ₂ (kt/wk)	NO _x (kg/wk)
Baseline	88.6 ± 0.3	90.8 ± 7.0	43.4 ± 3.6	$2.0 \times 10^{-2} \pm 2.8 \times 10^{-2}$	68.6 ± 0.6	8.5 ± 0.1	246.4 ± 0.3	167.6 ± 0.2
+10% Freight	111.0 ± 0.6	203.6 ± 1.2	105.5 ± 1.4	1.6 ± 0.1	222.7 ± 15.7	57.0 ± 4.1	276.4 ± 1.0	187.9 ± 0.6

¹ Note that in the simulation model, the TAP queue doubles as a section of road and as a queue for holding freight vehicles during TAP events. Minimum dwell time in the TAP queue is 8.5 min and corresponds to free-flowing traffic.

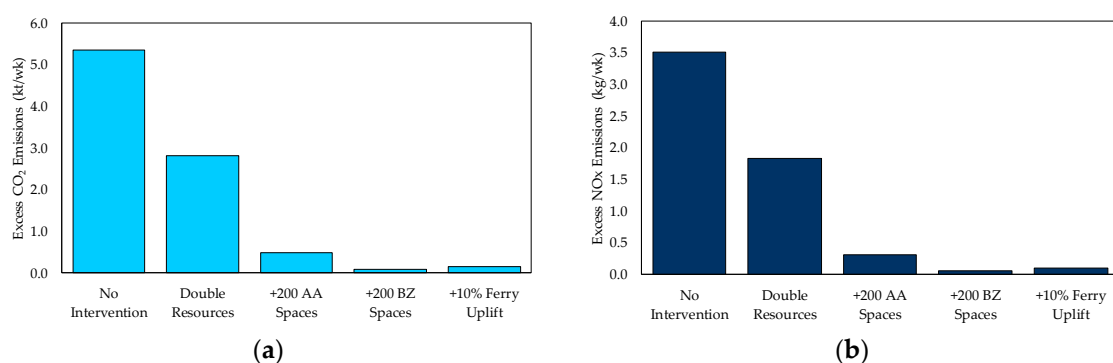
3.2. Interventions to Manage Freight Growth

Having quantified the impacts of a relatively modest increase in traffic volume, our next step was to identify and evaluate possible interventions to mitigate these impacts. Realistic interventions for dealing with a 10% freight growth scenario include increasing the number of PAF and check-in booths, adding space to the assembly area, adding space to the buffer zone, and increasing ferry uplift. Interventions that increase the number of PAF/check-in booths or increase space for holding vehicles could either be achieved by re-purposing other areas within the Port (e.g., demolishing existing buildings to create space) or through costly reclamation of land from the sea. Table 3 reports the effectiveness of various interventions to deal with increased freight volumes. Excess emissions of CO₂ and NO_x for each intervention are displayed in Figure 7.

Table 3. Traffic flow metrics for potential interventions to manage 10% growth in freight traffic.

Scenario	Time in System (min)	Buffer Zone			TAP Queue ¹			CO ₂ (kt/wk)	NO _x (kg/wk)
		Max Size (FEUs)	Max Dwell (min)	No. TAPs (per wk)	Max Size (FEUs)	Max Dwell (min)			
No Intervention	111.0 ± 0.6	203.6 ± 1.2	105.5 ± 1.4	1.6 ± 0.1	222.7 ± 15.7	57.0 ± 4.1	276.4 ± 1.0	187.9 ± 0.6	
Double Resources	110.2 ± 0.6	196.8 ± 1.6	102.7 ± 1.7	1.3 ± 0.1	184.2 ± 15.3	46.8 ± 4.0	273.9 ± 0.7	186.2 ± 0.5	
+200 AA Spaces ¹	110.7 ± 0.6	169.2 ± 6.5	83.9 ± 3.3	0.5 ± 0.1	93.4 ± 7.5	17.5 ± 2.5	271.5 ± 0.4	184.7 ± 0.2	
+200 BZ Spaces ²	111.0 ± 0.6	281.8 ± 8.7	130.6 ± 3.8	$1.0 \times 10^{-2} \pm 2.0 \times 10^{-2}$	74.6 ± 0.8	8.8 ± 0.3	271.1 ± 0.3	184.4 ± 0.2	
+10% Ferry Uplift	87.2 ± 0.3	138.6 ± 7.7	61.2 ± 3.6	0.2 ± 0.1	78.4 ± 4.0	10.6 ± 1.2	271.2 ± 0.3	184.5 ± 0.2	

¹ AA refers to the assembly area with additional space measured in FEUs. ² BZ refers to the buffer zone with additional space measured in FEUs.

**Figure 7.** (a) Excess CO₂ emissions per week and (b) excess NO_x emissions per week for potential interventions to manage 10% growth in freight traffic. Note that CO₂ emissions are measured in kilotons (kt) per week, while NO_x emissions are measured in kilograms (kg) per week.

Some important insights are drawn from the results shown in Table 3 and Figure 7. The first is that PAF and check-in are not significant constraints on the system given the rather modest change in traffic flow metrics in response to doubling PAF and check-in processing rates. Buffer zone usage and dwell time, for example, remain virtually unchanged. There is, however, a small drop in the number of TAPs per week (−0.3), a noticeable decrease in both TAP queue size (−39 FEUs) and dwell time

(−10 min), and a sizeable drop in excess emissions (−2.5 kt of CO₂ and −1.7 kg of NO_x per week). What this implies is that there is at present sufficient physical capacity to handle a 10% growth in freight traffic. It is merely the case that staffing levels within the Port may simply need to rise on certain days to keep pace with the increased volumes of freight vehicles.

A second key insight is that increasing space, either in the assembly area or buffer zone produces the desired effect of internalizing queues within the Port. Both interventions significantly reduce the number of TAPs per week, maximum TAP queue size, and excess emissions of CO₂ and NO_x. However, not all space is equal in terms of impact. Specifically, increasing space for vehicles in the buffer zone is much more effective at reducing queuing outside the Port than increasing space in the assembly area (Table 3, Figures 7 and 8). Compared to the no intervention scenario, adding 200 FEU spaces to the assembly area reduces the expected number of TAPs per week from 1.6 to 0.4 (an order of magnitude decrease), while adding 200 FEU spaces to the buffer zone reduces this to 0.01 (two orders of magnitude decrease). Over a month, this translates to approximately two TAPs by adding 200 spaces to the assembly area versus zero TAPs by adding the same amount of space to the buffer zone. Meanwhile, maximum TAP queue size is reduced from 223 to 93 freight vehicles (−130 FEUs) by adding 200 spaces to the assembly area and all the way down to 75 freight vehicles (−148 FEUs) by adding 200 spaces to the buffer zone. In terms of excess emissions of CO₂ and NO_x, these fall from 5.4 kt and 3.5 kg per week, respectively, to 0.5 kt and 0.3 kg per week (91% reduction) by adding 200 spaces to the assembly area and even further to 0.1 kt and 0.1 kg per week (97–98% reduction) by adding 200 spaces to the buffer zone.

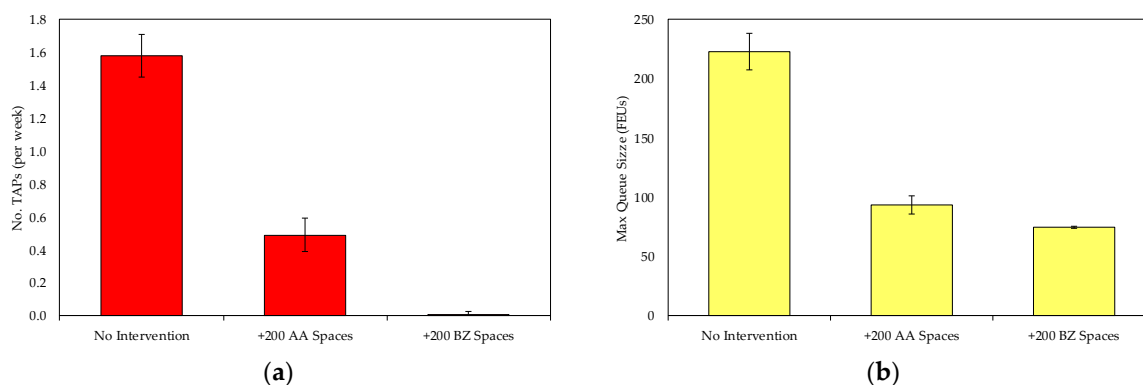


Figure 8. (a) Expected number of TAPs per week and (b) maximum size of the TAP queue for the no intervention, add space to the assembly area (AA) and add space to the buffer zone (BZ) planning scenarios in response a 10% growth in freight traffic.

Intuitively, this sort of result makes sense due to the flexible nature of the buffer zone, which can be used to buffer any single operator’s traffic or a specific type of traffic, thus allowing other vehicles to bypass the queue. The assembly area, on the other hand, is located low in the chain of steps for processing vehicles through the system and, therefore, does nothing to alleviate transient queues caused by the fluctuation of processing rates at steps higher in the chain (e.g., at PAF or check-in). Indeed, a proportion of real-life TAPs are caused by issues at border control or check-in (e.g., due to computer system failures or slower processing associated with heightened security levels). These types of events are not captured in the simulation model, which suggests that the results shown here underestimate the value of buffer zone space at the front of the Port.

A final, perhaps unsurprising, finding is that increasing ferry uplift is perhaps the best solution for dealing with increased freight volumes in the long-term. Increasing uplift in step with traffic demand is the only intervention that minimizes queuing both in and outside the Port. Compared to increasing buffer zone space, increasing uplift by 10% not only produces similar maximum TAP queue sizes (78 vs. 75 FEUs), maximum TAP dwell times (10.6 vs. 8.8 min) and excess CO₂ emissions (0.2 kt vs. 0.1 kt), but also results in the lowest usage of the buffer zone (both in terms of maximum queue size and dwell

time) among the interventions considered. In addition, unlike any of the other scenarios, increased ferry uplift also reduces overall time in the system from 110–111 min (all other scenarios) to 87 min. On the other hand, while it should be pointed out that increasing ferry uplift does result in a slightly higher number of TAPs per week compared to adding space to the buffer zone intervention (less than 0.2 vs. 0.01), over a month the overall number of TAPs remains small (approximately 0.7 per month).

It is worth mentioning that in the current model, increased uplift was implemented by simply increasing the capacity of each vessel by 10%. We acknowledge that adding larger vessels to the fleet would place additional strains on the assembly area and buffer zone, since larger numbers of vehicles would be arriving and waiting for the next (larger) vessel. Alternatives such as increasing the frequency of sailings or adding a few additional vessels, however, would mitigate against this to a large extent.

Additional testing of the simulation model assuming a 30% growth in freight traffic (results not reported here) only further reinforces the importance of ferry uplift. Increasing uplift by 30% is sufficient to handle increased traffic of this magnitude without the need for additional space or new infrastructure. However, a 30% increase in freight traffic without a concomitant increase in uplift would exceed the physical capacity of the Port.

3.3. Sensitivity Analysis of Check-in Processing Times

As illustrated by the analysis above, Port infrastructure and processes are sufficient to handle present-day freight volumes. Furthermore, a 10–30% increase in growth could be accommodated by increasing buffer zone space within the Port and/or increasing ferry uplift. Under such circumstances, neither PAF nor check-in would form a bottleneck as long as processing rates remain the same.

As part of robust masterplanning, one might want to challenge the assumption that processes will not change in the future. While the majority of changes such as increased digitization and automation tend to improve throughput, there are two possible scenarios which could make processing times worse: (1) sustained increase in security, which would result in increased time for border control checks, and (2) expanded administrative requirements at check-in, for example filling in additional customs documentation as part of a post Brexit world. It is hard to forecast what changes in processing times might be, particularly for the latter scenario, since there is not any reliable data on which to base projections. Sensitivity analysis, however, provides a vital tool for investigating potential impacts over a range of possible changes to model inputs.

To this end, the effect of increased time to process vehicles at check-in was investigated on top of a 10% growth in freight traffic. As in the previous analyses, it is assumed that there are no restrictions on the availability of check-in booths (i.e., all booths are manned continuously throughout the week) and that up to 80% of them are devoted to freight. Results are shown in Figure 9.

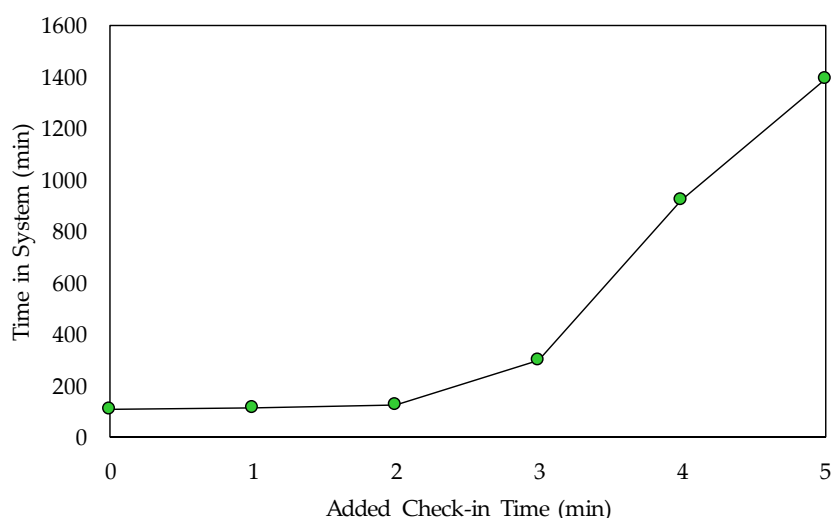


Figure 9. Time in system as a function of average check-in time given 10% growth in freight.

If processing times at check-in booths increased by one minute, average time in the system would be little affected, increasing by just two minutes. Increasing check-in times by two minutes would also appear to be tolerable, with an average time in system going up by 14 min. However, this underestimates the true impact since it is assumed that staffing is unconstrained and queues are initially empty at the start of each one-week run of the model. In reality, staffing may be less than ideal and there may be carry-over of vehicles from week-to-week once large queues form. Indeed, separate full year model runs that incorporate carry-over indicate that even a two-minute increase in processing times produces considerable queuing and long delays for freight traffic. In any case, what is perfectly clear is that increasing processing time by just three minutes is sufficient to increase time in the system to almost 300 min, which not only exceeds the Port's capacity, but also exceeds the capacity of TAP and necessarily triggers Operation Stack/Brock. Adding a full five minutes to check-in time, meanwhile, causes average time in the system to reach almost 1400 min (>23 h) and produces queues that never clear. To put these figures in context, the waiting time at the "frictionless" Norway–Sweden border is reported to be on the order of eight minutes [37].

3.4. Additional Uses of the Model

Whilst the primary focus of the present modeling study is on long-term infrastructure planning, it should be noted that the model can just as easily be used to examine the potential effects of shorter-term stressors on the system and evaluate appropriate tactical mitigation strategies. One such stressor is annual ferry refit, in which a vessel is removed from service temporarily for planned maintenance and upgrading. Results showing the impact of a vessel refit are shown in Figure 10 and Table 4.

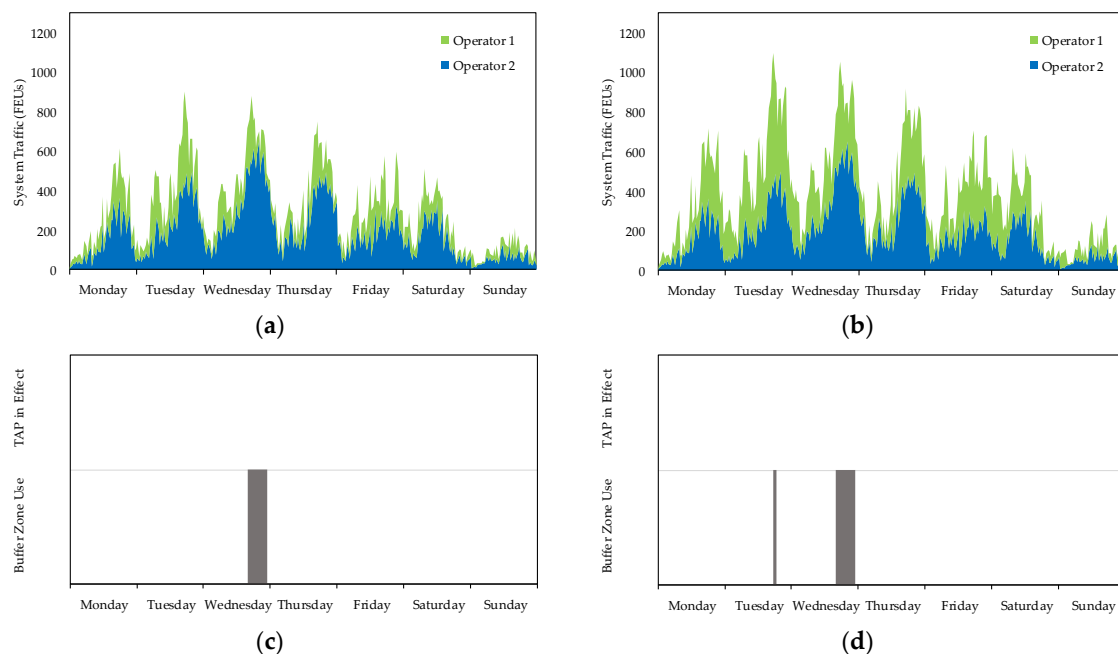


Figure 10. (a) Simulated Port traffic by ferry operator (blue and green) over a typical week under baseline conditions and (b) during a ferry vessel refit, along with (c) buffer zone (grey) and TAP use (red) under baseline conditions and (d) during a ferry vessel refit.

As seen, the system is only moderately affected by a vessel refit. While the total number of vehicles in the system does increase during a vessel refit (see Figure 10), going from a peak of approximately 900 to 1100 FEUs, TAP would not be expected to occur and there is only limited additional use of the buffer zone (one day for normal conditions, two days for vessel refit). Overall, traffic metrics for the

two scenarios are similar (see Table 4), with the only significant difference being that total time in the system increases by 25% (from 89 to 111 min).

Table 4. Traffic flow metrics for the base case and vessel refit scenarios.

Scenario	Time in System (min)	Buffer Zone		TAP Queue		
		Max Size (FEUs)	Max Dwell Time (min)	No. TAPs (per wk)	Max Size (FEUs)	Max Dwell Time (min)
Baseline	88.6 ± 0.3	90.8 ± 7.0	43.4 ± 3.6	2.0×10^{-2} $\pm 2.8 \times 10^{-2}$	68.6 ± 0.6	8.5 ± 0.1
Vessel Refit	111.4 ± 0.6	95.9 ± 6.2	44.9 ± 3.3	1.0×10^{-2} $\pm 2.0 \times 10^{-2}$	68.6 ± 0.6	8.5 ± 0.1

In principle, changes to the port infrastructure or operations could be investigated, similar to the analysis carried out in Section 3.2, to help identify appropriate strategies to minimize disruption at the Port during vessel refits in combination with other incidents causing short-term reduction in system capacity (e.g., staff shortages and/or extended security checks) to ensure the Port continues to meet its economic, social and environmental goals.

4. Discussion

This study describes how simulation modeling and analysis are being used at the Port of Dover to address economic, social, and environmental trade-offs involved with port masterplanning. It contributes to the scientific literature by focusing on road traffic in a ro-ro port and by providing basic insight into the interplay between the use of space and processes that influence port performance.

The study initially began during a period of high uncertainty for the Port, brought about by incidences of terrorist attacks in France, a spike in illegal migration, and the Brexit vote, which focused attention on understanding the implications of potential new border control, customs, and inspection regimes. The tensions involved in port masterplanning have been pointed out previously [38,39]. Investing in new infrastructure has repercussions that are long lasting, but decisions often need to be taken during periods of uncertainty during which forecasts vary widely. This highlights the value of options-based valuation, which emphasizes the importance of phasing, deferring, abandoning or adapting projects. Although the analysis presented here does not employ options valuation, our work has nevertheless stimulated ‘options thinking’ among senior managers at the Port and reinforced the need to adapt to changing opportunities and threats [40].

The discrete-event simulation approach used here is valuable for gaining high-level insights about traffic flow patterns and where and why queues build up in a system. One limitation of using discrete-event simulation is that it does not represent interactions between moving vehicles as well as agent-based models do. Further work using detailed agent-based models of specific areas of the system might help to verify that interventions identified with our discrete-event model for improving traffic flow perform as expected. Alternatively, developing a system dynamics approach might be appropriate for larger-scale modeling of cross-channel traffic flows by incorporating Eurotunnel and possibly other ports in the UK and continental Europe. Another interesting line of research would be to model an expanded set of interventions aimed at reducing queuing traffic, including implementation of the “dry port” concept [41]. Dry ports are used to move certain seaport functions inland and are shown to be effective in alleviating space constraints and improving environmental performance [42].

A noteworthy aspect of our study is the use of a queuing metric (TAP) as the primary KPI, both as a measure of overall system efficiency and as a measure of local community and environmental sustainability. The ability to use TAP to hold freight outside the Port is an immensely valuable means of managing port traffic. At the same time, reducing occurrences of TAP when possible reduces inconvenience to the local community and reduces direct staff cost of active traffic management. Minimizing traffic queues also helps to reduce the environmental impacts of port traffic, including air pollutant and CO₂ emissions, which will be vital in the future as the Port strives to meet its

environmental obligations and become a “green port” [43]. The use of TAP as a KPI contrasts with other simulation studies dealing with port investment planning (e.g., [44]), which use more typical financial metrics like EBITDA (earnings before interest, tax, depreciation and amortization). The TAP metric, by comparison, relates directly to two of the three pillars of sustainability (social and environmental), which can then be traded off against the third (economic) by considering investments needed to reduce TAP.

One of the main benefits of the research presented here is in discovering and illustrating some guiding principles that can be applied to port masterplanning more generally. As an example, our analysis of the Port of Dover showed the critical role of ferry uplift (i.e., the rate at which vehicles are removed from the system by ferries) as the main determinant of overall queuing in and transit through the system. Increased uplift is only achieved by adding more ferries and services of the current vessel type or by replacing some portion of the fleet with larger ferries, which might even require fewer services. Which is preferable would depend on a more detailed financial analysis of the costs involved and the environmental impacts.

One of the key messages we wish to emphasize is the value of flexibility. Specifically, space that can be used flexibly, either for multiple traffic types, ferry operators, or activities, is far more valuable than dedicated space, which cannot be readily switched to meet fluctuations in demand. This is clearly illustrated by the far greater reduction in traffic congestion that could be achieved by increasing buffer zone space to hold vehicles at the front of the system compared to increasing assembly area space for embarkation at the rear of the system. With added buffer zone space, transient increases in arrivals (immediately upstream of the buffer zone) and short-term reductions in processing speed at border controls or check-ins (downstream from the buffer zone) can both be accommodated for by space at the front of the system. Generalizing beyond this, it seems logical that under conditions of uncertainty, layouts and buildings that can be changed and re-purposed, provide greater value and resilience than permanent or fixed structures.

Looked at more generally, a potentially useful way to interpret our findings is within the context of the theory of constraints [45,46]. The guiding approach of our analysis was to look for those constraints which, if lifted, would have the largest effect on system performance. Interestingly, while ferry uplift is an obvious constraint governing total traffic throughput, relaxing constraints on space within the Port can be equally effective at reducing TAP and traffic congestion.

Finally, our analysis confirmed that the ability of the Port to clear traffic out of the system is strongly influenced by vehicle processing times. Even moderate increases in check-in times are not sustainable given the Port’s current physical capacity. The practical implication of this is to emphasize the extent to which technological improvements, such as automated check-in and license plate recognition, may be essential to speed up processing and improve future traffic fluidity.

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