Proceedings of the 2016 Winter Simulation Conference
T. M. K. Roeder, P. I. Frazier, R. Szechtman, E. Zhou, T. Huschka, and S. E. Chick, eds.

TRAFFIC SIMULATION MODEL FOR PORT PLANNING AND CONGESTION PREVENTION

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ABSTRACT

Effective management of land-side transportation provides the competitive advantage to port terminal operators in improving services and efficient use of limited space in an urban port. We present a hybrid simulation model that combines traffic-flow modeling and discrete-event simulation for land-side port planning and evaluation of traffic conditions for a number of what-if scenarios. We design our model based on a real-world case of a bulk cargo port. The problem is interesting due to complexity of heterogeneous closed-looped internal vehicles and external vehicles traveling in spaces with very limited traffic regulation (no traffic lights, no traffic wardens) and the traffic interactions with port operations such as loading and unloading cargos. Our simulation results show interesting decision-support scenarios for decision makers to evaluate future port planning possibilities and to derive regulation policies governing the port traffic.

1 INTRODUCTION

There has been an increased trend in the employment of smart port technologies to accommodate the changes and increasing trade competitions among the seaports. Ability to respond to carriers' berthing requests, and to provide safe and efficient cargo loading and unloading operations are examples of key performance indicators for port operators. Hence, port terminal operators need to make better decisions and plans in short-term to long-term periods to support the entire ocean-to-cities value chain.

Land-side port planning becomes an important aspect in this value chain, facilitating movement of cargos from land to sea and vice versa, which in turn affects berthing activities, port-stay, and customer satisfaction. Berth scheduling and resource assignment optimization at the quayside are examples of well-studied problems in this value chain, especially in the application area of container ports. However, we found few existing works with applications to other types of port terminals such as bulk terminal. In our study with a real-life case, we found that traffic flow is a complex and critical aspect that influences the performance of the port operations. Unlike a container port where all cargos are containerized in boxes, the nature of the goods handled in a bulk port is highly varied. The complexity is further exacerbated due to uncertain vessel arrivals, weather-dependent loading and unloading to/from vessels, and heterogeneous types of equipment and vehicles required to handle the movements of goods in and out of the port. This results in complex traffic flow analysis which impacts the performance of the port operations.

In this paper, we study a real-life case of a bulk cargo port terminal where we perform an evaluation of our modeling and simulation of port traffic based on its typical operation activities. The studied port encounters challenges in planning due to a decentralized operating business model in its multi-purpose port terminal environment. We proposed a simulation-based solution that quantifies evaluation of traffic operation under different throughput and operation scenarios for ports to enhance operation processes for higher efficiency and facilitate traffic policy-making for future development of the port.

978-1-5090-4486-3/16/$31.00

We propose a hybrid simulation framework that comprises of a traffic-flow model and discrete-event model. Our contributions are two-fold. Firstly, the ability to seamlessly integrate both traffic modeling and a discrete-event simulation. Secondly, we extend a microscopic car-following model to effectively and efficiently handle junction management in an unregulated condition (no traffic lights and no traffic wardens). The traffic flow model includes dynamic modeling of road networks (so that port can be reconfigured for future scenarios), modeling of drivers' behavior (to consider behaviors of different types of vehicles supporting various port operations) and the proposed efficient junction management. The discrete-event simulation provides the scenarios for the various port operations such as berthing and cargo handling activities. The port operations affect the traffic conditions and traffic policies affect the efficiencies of the port operations. Both traffic and port operations are interlinked. The interdisciplinary interaction evaluation is interesting and novel as most of the existing literature we found covers either traffic evaluation or port operation efficiencies. In addition, the output of our simulation model provides analysis and visualization for decision evaluations, and allows decision-makers to derive policies that better manage the traffic conditions in the port.

2 CASE STUDY

A real life study is conducted at a selected bulk port located within a city in the Asia Pacific region. The selected bulk port handles break bulk (e.g., steel), dry bulk (e.g., cement, sand) and liquid bulk (e.g., chemical, multi-purpose oil). Three types of human participants are being considered in this case study, namely *terminal operator*, *stevedore* and *consignees*. In our context, we have a port *terminal operator* which operates a terminal within a port. In the studied terminal, the cargo handling is mostly managed by *stevedores* and some facilities are leased to the various business operators (known as *consignees*) to carry out their operation in the port. Other than the members of the terminal operator, stevedores and employees of consignees make up a large percentage of port users. An example of a consignee in the port is a cement company that takes in raw cement to produce cement-related products for the construction industry.

The operation management of the port activities such as loading and unloading of cargos are largely decentralized, and managed by stevedores and consignees. Being decentralized, the terminal operator is unable to fully control the traffic generated by its port users. However, the terminal operator has control over the facilities (berths, yards, warehouses, buildings, road network, equipment such as quayside cranes and conveyor belts) and overall spatial planning of the terminal. While the port experiences economic and growth transformations, the port operator is interested in evaluating future plans and ensure that these plans minimize congestion within the port. This situation makes the problem interesting as controlling traffic congestion in the port is a combination of spatial planning, resource assignment, and policies that in turn impacts the behavior of the port business users such as the stevedores and consignees.

The port's traffic comprises a heterogeneous mix of both internal and external vehicles. The internal vehicles form the closed-loop traffic as they stay within the port and do not exit the port. Typically, internal traffic is generated due to port operation activities such as loading/unloading of cargos between berth and storage location (e.g., yards, warehouses), cargo movements, and transportation for port users within the port. In addition to the closed-loop traffic, the traffic comprises the external vehicles (different types of vehicles carry different types of bulk cargo) entering the port through the port gates. The external vehicles support import or export activities or transport the port users to the work sites. An external vehicle may enter the port for a purpose such as unloading or picking up a cargo and then exit the port. It may also enter the port, park at a desired location or alongside road to wait for an order to pick up a cargo. A vehicle can stay in the port up to multiple days. Such behavior makes the traffic model complex and mathematically intractable. Hence, a simulation model is used to evaluate the traffic performance in the port with considerations of closed-loop traffic and special drivers behavior (e.g., waiting alongside a road) in a road network with minimal traffic regulations.

The selected bulk port provides historical berthing and traffic data and the business processes know-how on port terminal operations and management. The data provided are analyzed and provide inputs to the simulation model, e.g., vehicle arrival patterns. Due to the sensitivity of the data, detailed descriptions of the data has been omitted in this paper.

3 LITERATURE REVIEW

From traffic simulation model point-of-view, the traffic simulation can be divided into two categories: macro-simulation and micro-simulation. Two examples of existing macro-simulation model are cell transmission model (CTM) (Daganzo 1995) and Non-Local and Gas-Kinetic-Based Traffic Model (Treiber et al. 1999). The main idea of macro-simulation is to aggregate individual vehicles as a group of vehicles within a spatial area (known as a cell). For example, the CTM predicts the traffic flow over complex networks based on the density and flow through every predefined cell. The state of the network is updated based on groups of vehicles within all the cells. Non-Local and Gas-Kinetic-Based Traffic Model follows the same concept, except that the traffic equation is derived from a gas-kinetic traffic model. The advantage of macroscopic traffic models is that they simplified the traffic dynamics without considering the complex interactions between drivers. For instance, there is no difference between multi-lane simulation and one-lane simulation when applying macro-simulation model. Macro-simulation typically has fast execution time.

In the agent-based micro-simulation category, there exists a large number of car-following models, including the Intelligent Driver Model (Treiber et al. 2000), Gazis-Herman-Rothery model (Chandler et al. 1958), safety distance models (Kometani and Sasaki 1959), linear models (Helly 1959), psychophysical or action point models (Michaels 1963). Most microscopic models assume that drivers affect the behavior of neighboring drivers. With the car-following approximation, the vehicles update their speed accordingly. For example, a typical method in intelligent driver model requires the calibration of distance to the front vehicle to achieve a desired velocity, safe time headway, maximum acceleration, desired deceleration and minimum distance between the fronts of the two vehicles.

To the best of our knowledge, there is no or limited literature related to traffic study that handles the complex non-homogeneous nature of bulk port terminal. There exists some traffic-related information for the container port terminals. Boer and Saanen (2014) proposed a simulation for terminal operating systems that supports planners in making plans about vessels, trucks and trains through plan validation. Yang and Takakuwa (2014) presented a procedure to construct simulation models of container terminal. There are also many studies related to automated guided vehicles (AGVs) within container terminals, e.g., Ye et al. (2000) describes parallel simulations of an AGV system.

In terms of availability of simulation software, there are a number of traffic related softwares such as VISSIM, TRANSIMS, MOVSIM (Ratrout and Rahman 2009). As we evaluate the software, we found our unique simulation requirements to simulate the traffic and operations in the port, and to include smart port technologies such as intelligent traffic routing and policies. As the traffic within the port is minimally regulated, a microscopic approach with ability to model drivers' irregular behaviors becomes an important need in our port simulation. In addition, we also found the need for a discrete-event simulation that handles the port operational activities (e.g., loading/unloading activities due to vessel arrival, picking up a cargo due to an incoming order for dry-bulk) that interacts with the traffic-flow simulation and vice-versa. As such, we propose a model that combines micro-simulation for traffic flow, along with discrete-event simulation model. In our final proposed model, we have also included an option to run the simulation in the macroscopic mode at the junctions to speed up the execution time.

4 PORT PLANNING SIMULATION FRAMEWORK

We propose an integrated framework that provides traffic-flow and discrete-event simulation that mimics the real-world scenario. The framework leverages on historical port data as input parameters to the simulation. Referring to Figure 1, the framework comprises a combination of two simulation models, namely Traffic-Flow Model and Discrete-Event Queue Model. The Traffic-Flow model is designed to model the road network, the driver behaviors on route selections and events that trigger changes to drivers' behaviors in certain manners (e.g., arrival of an order to pick up cement from the silo for export). The Discrete-Event Queue Model is designed to model the queues, service times and locations of the service stations (e.g., berth, warehouse and yard). The port vehicles have to stop at service stations to perform various tasks in the port.

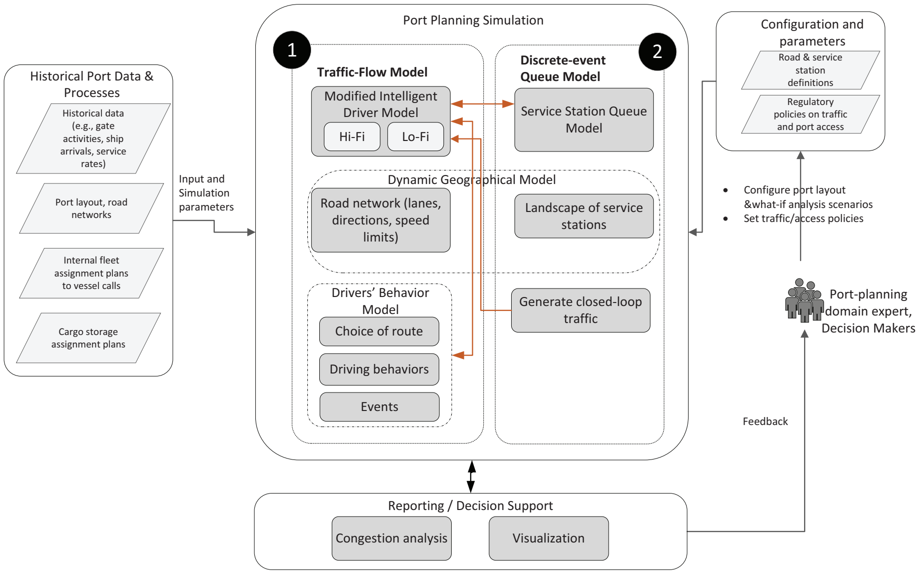


Figure 1: Port-planning Simulation Framework.

4.1 Dynamic Geographical Model and Discrete-Event Queue Model.

For clarity in understanding the Traffic-Flow Model in the subsequent sub-section, we will first explain the Dynamic Geographical Model and Discrete-Event Queue Model. Discrete-Event Queue Model generates port activities events such as arrival of vessel and arrival of an order to pick up cargo. The landscape of the entire port is modeled as a road network in the Geographical Model with multiple service stations. The road network, represented by a graph of nodes and arcs, is a network of lanes that are available in the port. Each road may contain multiple lanes. We also include the properties of each road, such as the directions and speed limits. Junctions are determined by intersection of two or more lanes. The gates, berths and storage locations are modeled as service stations. For example, when an external vehicle (e.g., cement truck) arrives at the main gate to pick up a cargo for import, it is being "served" at the gate for a period of time, then travels to a storage service station (e.g., a cement silo) to load the cargo. Upon completion, the vehicle travels to the main gate and exits the port. Each service station is modeled as a queue system. The type of queue system is defined based on our understanding (either from expert inputs of the port terminal operator or from generic sources) of the nature of the operation. For example, a cement silo which allows two vehicles to be served at the same time can be modeled as an M/M/2 queue system. The queuing systems are modeled and executed in the Discrete-Event Queue simulation model.

To meet the planning request of port terminal operator, our framework supports inputs from port planners to dynamically configure road networks and locations of service stations through grid-based coordinates that map back to the geographical positions. For example, in the case of inclusion of a new type of cargo, changes must be made to berth layout and also road network. In addition, decision makers can also set policies about port traffic and evaluate the outcome through our proposed port planning simulation. For example, port planners may decide that parking along certain busy roads is prohibited. The configuration of the port layout and policies are configurable to port planning scenarios. Port planners and decision makers can use the proposed simulator to evaluate the impact of traffic policies and efficiency of port operations of the given scenario.

4.2 Traffic-Flow Model

We extend the Intelligent Drivers' Model (Treiber et al. 2000) (IDM) and MOBIL lane-changing model (Kesting et al. 2007), by implementing a vertex coloring algorithm for simulating drivers' behaviors at the junctions without traffic lights. Then we configured the IDM to suit the scenario in the port with roads of shorter length and larger (in length and width) vehicles. We modeled various types of external vehicles (e.g., cement truck, car, prime mover, tipper truck, bus, lorry etc.), each with a time-varying non-homogeneous Poisson arrival process. The port's closed-loop internal vehicles (e.g., forklift, reach stacker, internal prime movers) do not have an arrival process but are triggered by operations events in the port. E.g., arrival of a steel vessel at berth number 15 may require 5 forklifts to unload the cargo and 5 internal prime movers to transport the steel cargo from this berth to an allocated open yard for storage.

IDM is a time-continuous vehicle-following model. It updates the acceleration of each vehicle by considering the following factors: distance to the front vehicle, desired velocity, safe time headway, maximum acceleration, desired deceleration, minimum distance, and vehicle length. Let v be the current speed, and s be the distance. Specifically, v_0^i is the desired velocity on a free road for vehicle type i. Vehicle type i's minimum desired distance between the front vehicle is represented by s_0^i. T^i stands for the desired time headway (for vehicle type i) to the vehicle in front. a^i and b^i are the maximum acceleration and comfortable braking deceleration (for vehicle type i) respectively. δ is an adjustment parameter, which is set to 4 according to Treiber et al. (2000). As port environment generally has low speed limits, the accelerations for loaded and unloaded vehicles have negligible differences. The equation for determining the acceleration of next time step is as follows:

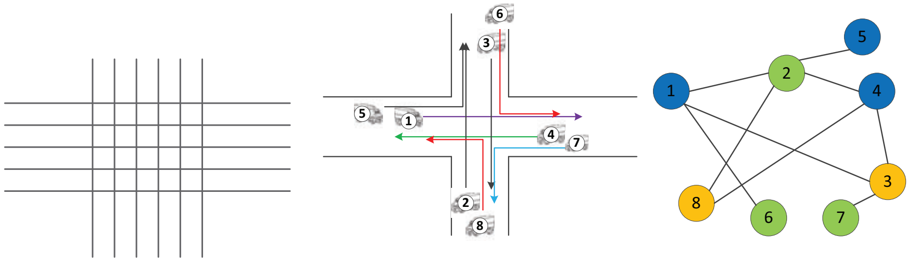
$$\dot{v} = \frac{\mathrm{d}v}{\mathrm{d}t} = a^i \left(1 - \left(\frac{v}{v_0^i} \right)^{\delta} - \left(\frac{s^*(v, \Delta v)}{s} \right)^2 \right), \text{with } s^*(v, \Delta v) = s_0^i + v T^i + \frac{v \Delta v}{2\sqrt{a^i b^i}}.$$

For a vehicle considering a lane change, the safety issue comes from the successive vehicles on the target and present lanes. MOBIL lane-changing model guarantees that after a change of lane, the deceleration of the successor vehicle on the target lane does not exceed a safe limit.

4.2.1 Vehicle Behavior in the Junction Area

IDM and MOBIL models, however, cannot fulfill all the requirements in a port. The main issue is the lack of traffic regulations such as traffic lights, roundabouts or any traffic wardens to direct traffic. The lack of traffic lights makes it difficult to simulate the traffic at the junction and the open yard area due to insufficient regularity. Illustrated in Figure 2, the first figure shows a typical port yard area with multiple lanes. Different vehicles may travel in this area in different directions. Transitional methods used to simulate traffic in junction without traffic lights are complex. For instance, if one applies the traditional lane-changing methodology (Khalesian and Delavar 2008), all the interactions between the vehicles must be checked. Multiple decisions are required, including both the vehicle movements and lane-change behavior. This method can easily lead to multi-cycle deadlock, as described in Ye et al. (2000).

The main innovation of our traffic-flow simulation model is the application of the vertex coloring method (Jensen and Bjarne 1994) to simulate the traffic in such an unregulated junction. It is simple and efficient. Supposing each vehicle is a node as shown in Figure 2c, if two vehicles have a potential possibility of conflict with each other, we add a link between them. The instruction for handling vehicles without collision at the non-regulated junction can be short-term or long-term. In a short-term instruction, we make the decision 1 second before the truck arrives at the junction area. A long-term instruction can last for $5-10$ seconds. Typically, in the port environment, the short-term instance is applied. Giving an example for the long-term instruction, truck 1 arrives at junction between 9:00:00-9:00:05 and truck 2 arrives at the same junction between 9:00:03-9:00:08 based on estimation of the speed of both trucks. We will add one link between truck 1 and truck 2 because the arrival interval of the two trucks has overlapped at some point of time. Next, we associate a positive weight to each vertex due to the different behavior of each vehicle/driver. The weight of the vertex depends on factors including the current speed (v), distance to the junction ($\bar{s}$), and aggression degree of the driver (a random number $\vartheta \in (0,1)$). The most aggressive driver passes the junction first. The formula we implemented is $\vartheta(0.3v + 40/\bar{s})$, parameters $0.3v$ and 40 are chosen based on traffic situation in the port. The parameters can be tuned according the real-life situations.



(a) Typical junction area (b) Eight vehicles travel in a junction (c) Translate to a vertex coloring problem

Figure 2: An example of the traffic at a junction.

In this way, the original problem is translated to a moving vertex coloring problem, where we assigned a color to each vertex in such a way that colors on adjacent vertices are different. Vehicles represented by the same color can move at the same time. For vertices with different colors, we apply a heuristic to determine which group can move first. The basic assumption is that the group with largest associated weight move first; others stop or slow down to avoid collisions. The details of the algorithm are described in Algorithm 1. Vehicles are assigned the colors in a greedy manner. Upon associating the vehicle's weight, we assigned colors one by one. In terms of notation, N is the number of vehicles in the graph, $\chi[1..n]$ is the priority sequence of the vehicles which is based on the associated weight of vehicle i. $c[1..m]$ stands for the assigned colors.

Algorithm 1: Heuristic for the vertex coloring problem in the simulation.

```
Input: Graph $G$ with $n$ nodes, simulation time duration $\bar{t}$. For a group of vehicles passing the
       junction area, and predefined sequence $\chi[1..n]$ which is based on the associate weight of
       vehicles, empty color set $c$
while $t < \bar{t}$ do
  Step 1: for $j = \chi_1$ to $\chi_n$, assign a color $c_j$ to the node
  Step 2: store the solution as $M(G, \chi, c)$
  Step 3: simulate vehicle movements for $t = t + 1$
          update new graph $G'$ based on new traffic situation at the junction
  Step 4: if ($G' \neq G$)
              compute $\chi'$ for $G'$
              $G \leftarrow G'$, $\chi \leftarrow \chi'$, go to step 1
          else, go to step 3
end while
```

4.3 Drivers' Behavior Model

From our interactions with the port terminal operator, we understand the need to have an extensive drivers' behavior model as the behavior of drivers in the port is dissimilar to the typical congested road network with regulations. For example, we modeled a Park-n-Wait Event, a scenario when a truck needs to wait for a cargo-loading instruction (e.g., the truck driver has not received an order from his office, the crane or silo is out of service). The truck cannot go directly to the service station yet. It will wait at a parking area or alongside a road near the service station location. Such behavior affects the traffic flow in the port and there are certain patterns when such behaviors are observed. E.g., more cement trucks are waiting along the path to the cement silos during peak hour of noon to 3pm on weekday to compete for a delivery order.

We also model the drivers' behavior for the internal closed-loop traffic to define the behavior of certain vehicles. When a steel vessel arrives at the berth, forklifts travel from their parking locations to the berth to unload the cargo from the vessel. During unloading period, forklifts affect the traffic at the berth only. Meanwhile, two possibilities might occur: (1) internal prime movers are dispatched to transport the cargo to a yard or (2) some external prime movers are dispatched to transport the cargo out of the port. Events are triggered by a defined probabilistic distribution of the likelihood of occurrence. Routes and drivers' behavior are configured as external parameters and probabilistic model is used to determine the driver's choice of route. An event can alter the driver's behavior.

5 SIMULATION

We developed a prototype of the Port Planning simulator with Traffic-Flow simulation and Discrete-event simulation based on our understanding with our case port terminal. We used the simulator to evaluate the performance of the port traffic under a set of what-if operation scenarios. The simulator takes in a combined information on historical arrival rates, operation process information and simulated internal traffic volume, and generates the simulated data for further analysis and refinement of decision parameters. The simulator is implemented in Java and executed on an Intel(R) Core(TM) i7-4790 3.6 GHz CPU 16 GB RAM computer.

5.1 Two Fidelity Levels of Simulation

The traffic in our scenario is highly complex as there is a need to consider external and closed-loop traffic, large number of resource assignment possibilities (e.g., crane allocation, yard allocation) and service stations variations. Running simulation that mimics the real scenario as close as possible can be computationally expensive and time-consuming. In order to improve performance of the simulation, we set up two fidelity levels of simulation, namely, high-fidelity (Hi-Fi) and low-fidelity (Lo-Fi).

In the Hi-Fi simulation, we model lane-changing behavior based on MOBIL model and junction area decision making based on our proposed coloring algorithm as described in Section 4. In the Lo-Fi simulation, we relaxed the complexity of the junction decisions by assuming all the vehicles travel at a given slow speed of 5 km/h, and ignore the potential conflict between vehicles. With the relaxation, we could increase the simulation time step by 3 times (one second). A comparison test (to be discussed in the next section) is applied to compare the performance provided by the two fidelity levels.

5.2 Evaluation Indicators

For our simulation output, we provide three evaluation indicators, namely **speed**, **percentage of congestion** and **entropy**. We explain how we calculate and derive speed and percentage of congestion in sub-section 5.2.1 and entropy in sub-section 5.2.2.

5.2.1 Congestion Analysis

As part of our simulation output, we measure average **speed** of the vehicles and the density of each road. These two measurements are standard measurements in traffic simulation literature. Next, using combination of speed and density, and taking references from Bauza and Gozálvez (2013), we derive at a set of congestion levels suitable for our application as per Table 1. Four levels of congestion are specified: free, slight, moderate, severe. We modified the speed and density parameters to adapt to the port environment. For instance, majority of the vehicles in the port environment has length much longer than normal cars and traveling at much lower speed as compared to vehicles on general public roads.

A congestion is defined as a situation where the combination of the average speed and density of the traffic on the road results in either *moderate* or *severe* state. **Percentage of congestion** on a particular road is then defined as a percentage of time that it is experiencing a *congested* state over the whole simulated time period.

Table 1: Levels of traffic congestion.

		Density (veh/km/lane, based on snapshot record per min)			
		low (20)	medium (40)	high (60)	very high (80)
Speed	very slow ($<$ 40% speed limit)	slight	moderate	moderate	severe
	slow ($\geq$ 40% speed limit)	free	slight	moderate	moderate
	medium ($\geq$ 60% speed limit)	free	slight	slight	moderate
	fast ($\geq$ 80% speed limit)	free	free	free	slight

5.2.2 Entropy-Based Evaluation

Entropy is a concept which originally arose from the study of the physics of heat engines (Carter 2000). It can be described as a measure of the amount of disorder in a system. For a high-discipline system, the entropy value is low due to high similarities between individuals. The entropy value increases as the system enters a disordered state. We use entropy to measure the diversity of the road/traffic network's traffic states (varies between free, slight, moderate, and severe state). The entropy evaluation can provide the operator a multi-dimensional view of the network traffic, and efficiently detect network abnormality by comparing the current network traffic against a baseline distribution.

To calculate the entropy value of *a road* during the last hour, we determine the congestion level ϖ (free, slight, moderate, and severe) every 5 minutes. Subsequently, we calculate the percentage of occurrences of the states ϖ. Then, we get the **entropy** value (H) by computing $H = -\sum_{i=1}^{4} \varpi_i \log_2 \varpi_i$. Similarly, one can also measure the diversity of the entire road network in a given time point (e.g., traffic condition at noon for the whole port) by applying the same logic and formula.

5.3 Simulation Replication Determination to Ensure the Stability of the Results

In order to ensure that we have sufficient simulation replications, we run a test to determine the stability of the results of our simulator. Non-parametric Wilcoxon signed-rank test is used to determine whether there are significant differences between different number of replications selected. The null hypothesis states that the difference between the replication sample sizes follows a symmetric distribution around zero, and tests against the two-sided alternative hypothesis.

We first run simulations with 4 operation scenarios (with different port traffic demand and drivers' behaviors) and 600 replications for each scenario for the time period between 11:00-14:00 (peak hours of daily port operation activities). We choose 600 as a sufficient large number to carry out this experiment. The replication samples are translated into 20 groups, group 1 includes 1, 2, …, 30 replications, group 2 includes 31, 32, …, 60 replications, until group 20 include the rest of the 570, 571, …, 600 replications. We then compare each group with group 20. We observed that from group 8 (include 210, 211, …, 240) to group 19, we are unable to reject the null hypothesis with p-values larger than 0.05, indicating no significant difference in the results produced using sample sizes between 240 and 600. Hence, we used 240 as the number of replications for our subsequent experiments.

6 EXPERIMENTS AND RESULTS

We run three types of experiments. Firstly, we compare the execution time between Hi-Fi and Lo-Fi simulations (see Section 6.1). Secondly, using Lo-Fi simulation, we run sensitivity analysis with a business scenario that the port experiences higher throughputs where more traffic movements are required to perform the increased loading and unloading activities (see Section 6.2). And finally, using Hi-Fi simulation, we evaluate a number of port policies that can be implemented to control and manage the traffic (see Section 6.2.1) for selected roads with expected congestion.

6.1 Results Comparison between the Hi-Fi and Lo-Fi

In this experiment, we run the simulation using Hi-Fi and Lo-Fi simulations based on 5 what-if operation scenarios when throughput handled by the port are increased, hence resulting in more traffic movements (increase of traffic of 0%, 25%, 50%, 75% and 100%) in the port. The simulation is run for the entire port with about 40 roads. For ease of comparisons, in our analysis, we select the 7 most commonly used roads at the peak hour of 12:00-13:00 and compare the execution time for both methods. We found that Lo-Fi is approximately 4 times faster than Hi-Fi. To evaluate if both methods yield the same results, we use the non-parametric Wilcoxon signed-rank test to determine whether there are significant differences between the Hi-Fi and Lo-Fi simulation approaches. The null hypothesis states that the difference between the two approaches follows a symmetric distribution around zero. Approaches are tested against the two-sided alternative hypothesis. The p-values based on speed, congestion, entropy are 0.804, 0.845 and 0.600 respectively, indicating significant differences. Knowing that there are significant differences, we measure the gap between the two simulation approaches. The gap between the two approaches are found to be within 6% (with an average of 3%) based on speed, congestion and entropy. With this experiment, we estimated that the Lo-Fi simulation yields results with less than 6% loss in accuracy. With this finding, due to the large number of roads in the port and to speed up simulation runs, we propose to use Lo-Fi simulation for identification of bottleneck in the port traffic. After we have identified the traffic bottleneck on specific roads, we then use the Hi-Fi simulation to evaluate policies that can be implemented to control and manage the congestion on the specific congested roads.

6.2 Sensitivity Analysis and Bottleneck Identification Based on Lo-Fi

In this experiment, we use Lo-Fi simulation on the same 5 what-if scenarios with increased traffic movements (by steps of 25% until traffic is doubled) in the port. The results showed that the congestion time period is 11:00 to 14:00 on daily pattern. Hence, we capture the simulation results for this time duration. While simulation is run for the entire port with about 40 roads, only 3 roads were identified as potential bottleneck of the whole network. The three roads (we refer to Road 1, Road 2 and Road 3 for simplicity of discussion) with congestion have varying length, i.e., 1.68km, 0.70km, and 0.80km. A longer congested road indicates more impact on the port operations. All of them are main roads and are common roads for many of the external and internal (closed-loop) vehicles.

Figure 3 shows the traffic conditions on the three roads based on our three indicators. The x-axis denotes the test instances of increased traffic scenarios. The y-axis refers to the three performance indicators as obtained from our simulation. From the graph, we see that when the traffic increases, the median speed decreases to near 0 for Road 1 and 2, implying that vehicles come to a stop and go very slowly at these two roads. However, the strange phenomenon is that the speed increases in Road 3. With the visualization tool in our framework, we found out that the traffic flow happened to be following a sequence of 1–2–3 (see Figure 4). When the speed on Road 2 is very low, few vehicles pass Road 2 to arrive at Road 3. Road 3 becomes relatively empty, hence the speed is higher on this road. In entropy-based analysis, the entropy value decreases when congestion increases. This is to suggest that Road and 1 and 2 are congested evenly throughout the entire length of the road while Road 3 consistently remains relatively free.

In addition, we performed another sensitivity analysis by varying the probabilistic parameters of the internal traffic. We found that the same 3 road have been identified as the potential bottleneck. Next, Hi-Fi simulation is applied to verify and investigate the details under the specified what-if scenarios.

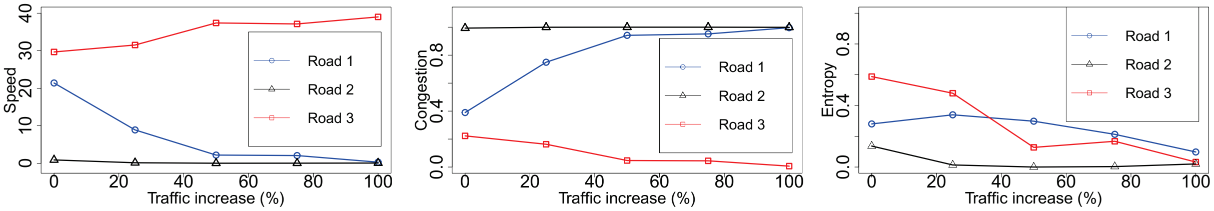


Figure 3: Sensitivity Analysis.

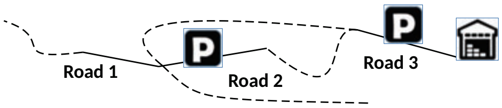


Figure 4: Layout of Road 1, 2 and 3.

6.2.1 Evaluation of Traffic Policies using Hi-Fi Simulation

On the selected 3 roads in the previous experiment, we would like to evaluate effects of the introducing intelligent guidance and governing policies by port terminal operator, to address the potential bottleneck under high traffic demand. In this experiment, we used the Hi-Fi simulation in this experiment to incorporate the various driving behaviors such as parking and change of lane and also junction management as described in Section 4.

We set up two types of policies: 1) path guidance policy (intelligent guidance) and 2) parking policy. For intelligent guidance, we consider a smart port scenario where path recommendation can be provided using road billboards to inform drivers on the conditions of the roads. The intelligent path guidance dynamically check the average speed of each road, and the road network is updated according to the approximate travel time on every road. System then make recommendations to the vehicle drivers to balance traffic on various roads. The list of tested policies in our simulation is as follows:

P1 intelligent guidance and no parking is allowed inside the port
P2 intelligent guidance with short-term parking being allowed inside port
P3 intelligent guidance with short-term and long-term parking being allowed inside port
P4 no intelligent guidance and no parking is allowed inside the port
P5 no intelligent guidance and short-term parking being allowed inside port

We compared the percentage changes(%) against the original setting where there is no intelligent guidance, but short-term and long-term parking are allowed inside port along the side of the roads. As found from previous experiment that if congestion occurs, congestion occurs for the whole affected road as the roads in the port are relatively short compared to a typical road outside the port. For ease of analysis, we focus on only speed and congestion percentage analysis in this experiment. Our results show that the deviation percentage can be more than 10 times higher than the indicator value of the original settings. This is because some of the original indicator value can be very low, e.g., speed at 2km/h.

From Table 2, the speed and congestion percentage are substantially decreased for Roads 1 and 2 when policies P1–P5 are applied. We observed that P1 and P4 are effective in resolving severe congestion problem for Road 1 and Road 2. However, when the port traffic increased by more than 50%, when Road 3 becomes congested, none of the policies can resolve the problem. The explanation is that Road 3 is found to be next to a number of busy service stations, such as the cement silos and other berth cranes operations. When the number of vehicles arriving at service stations is beyond the maximum capacity, the vehicles have to queue to load or unload the cargos at the service station. Such congestion occurred because the operational efficiency of the service stations is insufficient to cater for the demand.

From the output of P3, we found that the intelligent guidance policy cannot resolve the congestion problem of Road 2 as well as other policies. Intelligent guidance did help alleviate the congestion of

Table 2: Speed Dev (%) of different policies comparing to original setting.

		Speed						Congestion					
	Inc	BM	P1	P2	P3	P4	P5	BM	P1	P2	P3	P4	P5
R1	0	22	55	55	55	55	55	37	-99	-99	-99	-99	-99
	25	7	349	350	352	354	349	79	-99	-99	-99	-99	-99
	50	5	481	485	475	488	495	85	-99	-99	-98	-99	-99
	75	2	>1000	>1000	>1000	>1000	>1000	95	-99	-99	-85	-99	-99
	100	0	>1000	>1000	>1000	>1000	>1000	99	-99	-99	-75	-98	-99
R2	0	1	>1000	412	-42	>1000	355	99	-99	-12	0	-99	-8
	25	0	>1000	>1000	>1000	>1000	>1000	100	-99	-5	0	-99	-4
	50	0	>1000	>1000	68.03	>1000	>1000	99	-99	-4	0	-99	-9
	75	0	>1000	>1000	142	>1000	>1000	99	-99	-4	0	-94	-5
	100	0	>1000	>1000	448	>1000	>1000	100	-92	-6	0	-79	-6
R3	0	29	20	-35	-35	22	-23	24	-88	97	100	-94	63
	25	33	-15	-71	-72	-16	-66	13	-34	420	451	-3	427
	50	33	-56	-82	-83	-42	-89	13	202	473	481	84	554
	75	35	-77	-88	-88	-81	-85	7	695	959	>1000	898	931
	100	38	-87	-95	-90	-91	-91	1	>1000	>1000	>1000	>1000	>1000

"R1", "R2" and "R3": Road 1, 2, and 3. "Inc": increase of traffic. "BM": the benchmark we compared against.

Road 1 by directing some vehicles to Road 3. Policies P2 and P5 can reduce the congestion level of Road 2 by forbidding long-term parking inside the port. P1 and P4 (both do not allow parking) are slightly better in alleviating congestion than P2 and P5 (both applying intelligent guidance). Moreover, P1 is better performing than P2 and P5; while P4 is better performing than P5. This indicates that forbidding parking (along the side of the roads) policy is the most effective policy for the congestion problem except for the road nearest to the service stations where vehicles have to queue.

With the analysis, we showed that our simulator helps decision makers identify the effectiveness of policies P1 or P4, where no parking is allowed. To reduce the congestion level near the service stations, one would have to look into improving the operational efficiencies and resource assignments of the service stations to better service the incoming demand.

7 CONCLUSION

In this paper, we proposed a simulation framework that combines the traffic-flow modeling and discrete-event modeling for evaluation of port traffic based on port operation activities. An integrated framework is important due to the interactions and impact of operations on traffic and vice versa. In addition, we proposed an efficient and effective method to handle simulation at the junctions in minimally regulated road network which is important within the port. Our proposed framework can be used to provide decision support to policy makers about their decisions with various business scenarios such as increase in port throughput. Going forward, we look forward to include other what-if operation scenarios and to carry out quantitative validation with the real-world data in our test-bedding bulk port.

ACKNOWLEDGMENTS

This work is funded by the National Research Foundation Singapore under its Corp Lab @ University scheme.

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