



# Optimization of Stability Testing Methods for Port Gate Systems in a Specific Port

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## Abstract

With the ongoing advancement of information technology in the shipping sector, the stability testing of port gate systems has become increasingly critical. Traditional stability testing methods for gate systems suffer from deficiencies in theoretical quantitative analysis, low automation levels, and significant discrepancies between test results and real-world operational performance. In this study, we first employ the Local Outlier Factor (LOF) algorithm to conduct an in-depth analysis of weight datasets from gate processing across various business segments of a port, thereby laying the foundation for automated testing. Furthermore, we innovatively apply dynamics theory to analyze the stability of container gate systems, establishing a flow model that achieves high accuracy in predicting time-dependent variations in gate throughput. This approach bridges the gap between theoretical analysis and practical validation, offering a systematic methodology for enhancing the reliability of port logistics operations.

## Keywords

Stability testing; Local Outlier Factor (LOF) algorithm; Dynamics theory; Throughput prediction model

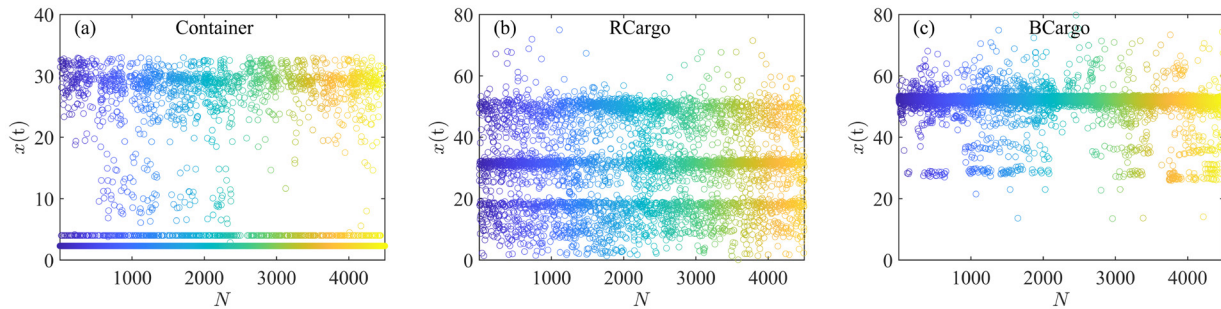
## 1. Introduction

With the rapid advancement of information technology in the maritime industry, stability testing of port gate systems has become increasingly critical. Under growing operational pressures, the productivity of ports—particularly those handling multiple operational modes—has become heavily reliant on the stability of their gate systems [1-4]. In recent years, various testing methodologies for port gate systems have emerged, yet most remain predominantly focused on peak-load pressure testing of associated software systems and manual inspection-based clearance verification processes. These conventional stability testing approaches suffer from low automation, fragmented implementation, and a lack of theoretical underpinnings, resulting in significant discrepancies between test outcomes and actual operational performance, thereby yielding suboptimal validation efficacy.

In this paper, our study investigates gate systems across diverse operational modes in a specific port, conducting a comparative analysis with conventional stability testing methodologies. Initially, we implemented the Local Outlier Factor (LOF) algorithm to perform an in-depth analysis of weight datasets derived from gate transaction processing [5]. Building upon this, an automated testing framework targeting weight measurement anomalies was developed, which demonstrated exceptional efficacy in identifying systemic deviations. Furthermore, leveraging principles from dynamics theory, we constructed a throughput prediction model capable of high-precision temporal forecasting of gate traffic patterns. This model was subsequently integrated with stability criteria to analyze container gate operations, achieving two critical advancements: (1) quantitative stability assessments under fluctuating cargo volumes, and (2) operational resilience evaluations across multimodal service scenarios.

## 2. Dataset Analysis

The port in question operates three distinct operational modes: container handling, roll-on/roll-off (Ro-Ro) cargo, and breakbulk cargo, each supported by dedicated gate systems tailored to their specific logistical requirements. Leveraging operational records from these heterogeneous service scenarios, we conducted preliminary statistical analyses to construct a comprehensive dataset of truck weight measurements processed through the gates. The aggregated data, as visualized in Figure 1, reveals significant modal-specific variations in weight distribution patterns, providing critical insights for subsequent anomaly detection and system stability evaluations.



**Figure 1. Weight distribution characteristics across multimodal gate operations: (a) Container gates exhibit bimodal distribution due to empty/full container differentiation; (b) Ro-Ro gates show leptokurtic patterns aligned with standardized vehicle loads; (c) Breakbulk gates demonstrate high variance reflecting heterogeneous cargo compositions.**

As illustrated in Fig.1, (a), (b), and (c) respectively depict the operational scenarios of container gate systems, roll-on/roll-off (Ro-Ro) cargo gates, and breakbulk cargo gates. As evidently shown, distinct distribution patterns emerge in truck weight data across different operational sectors. Notably, container gate systems exhibit the most well-defined weight distribution characteristics. Consequently, we focus on container gate systems as the primary research subject, subsequently applying the LOF algorithm to conduct an in-depth analysis of their weight datasets.

Initially, we perform data filtration on dataset (a). Given that values 2.3 and 4 collectively account for 65% of the total data volume, these specific entries are systematically excluded prior to computing the LOFs for the remaining dataset. Subsequently, we employ Equation (1) to calculate the k-reachability distance for each data point within its k-distance neighborhood, defined as:

$$RD_k(o, p) = \max(\{o\}, d(o, p)). \quad (1)$$

$p$  denotes the target data point and  $o$  represents neighboring points within its k-distance boundary. This preprocessing step effectively mitigates density estimation biases caused by high-frequency values. After that, we obtain the k-th local reachability density (LRD) for each data point using Equation (2), defined as the inverse of the average k-reachability distances within its neighborhood:

$$LRD_k(p) = 1 / \left( \frac{\sum_{o \in N_k(p)} RD_k(o, p)}{|N_k(p)|} \right). \quad (2)$$

Where,  $N_k(p)$  denotes the k-nearest neighbors of point  $p$ , and  $RD_k(o, p)$  is the reachability distance defined in Equation (1). This metric quantifies the local density distribution characteristics critical for anomaly identification. Finally, we compute the LOF for each data point using Equation (3), which represents the relative density deviation of a point compared to its k-nearest neighbors:

$$LOF_k(p) = \left( \frac{\sum_{o \in N_k(p)} LRD_k(o)}{|N_k(p)|} \right) / LRD_k(p). \quad (3)$$

Where,  $LRD_k(p)$  denotes the local reachability density defined in Equation (2). This metric identifies anomalies when  $LOF_k(p) \gg 1$ , indicating substantially lower density at point  $p$  relative to its neighborhood. The resultant distribution of LOF values for the filtered container gate dataset is shown in Figure 2.

As demonstrated in Fig.2, the LOF approaches unity ( $LOF \approx 1$ ) near the weight value of  $x = 29$  tons. Consequently, representative data points were systematically selected from the LOF distribution for subsequent weight measurement error testing, with the optimal candidate registering 29.15 tons, aligning with the theoretical density expectation for normal operations.

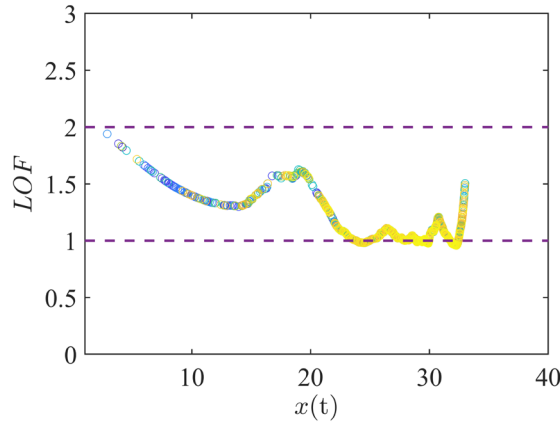


Figure 2. LOF Distribution Profile.

### 3. Weight Measurement Error Testing

Weight measurement error testing constitutes the cornerstone of gate system stability evaluation. As mandated by regulatory authorities, the discrepancy between pre-declared cargo weights and in-motion weighbridge measurements must not exceed prescribed thresholds, with non-compliance incurring administrative penalties. The weight error can be deduced from Equation (4):

$$F_t = \frac{|x_p - x_0|}{x_0} \tag{4}$$

Where,  $x_0$  and  $x_p$  respectively denote declared weight and actual weighbridge measured weight. In real-world operational scenarios, most trucks entering port gate systems lack pre-entry weighbridge verification, making precise cargo weight determination practically infeasible. Even for the minority of trucks subjected to preliminary weighing, systemic discrepancies between weighbridge systems frequently trigger risk control alerts upon gate entry, leading to unwarranted penalties. Consequently, simulating authentic truck entry conditions, particularly addressing how cargo weight declarations should be processed under inherent measurement uncertainty, is critical for stability testing. Traditional testing approaches, which rely on manual judgment and lack scientific analytical frameworks, exhibit high false-positive rates and fail to achieve automated declaration, significantly impairing operational efficiency. Based on our data-driven findings, we propose adopting representative data points as standardized declaration constants within the system, which can reduce the probability of triggering risk control alerts by approximately 80% through computational optimization. By implementing Equation (4) for constant derivation, the results, as shown in Figure 3, demonstrate the efficacy of this approach in reconciling declaration accuracy with operational pragmatism under real-world constraints.

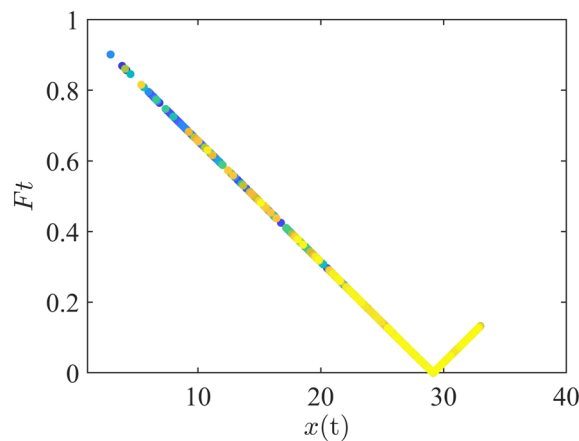


Figure 3. Weight Measurement Error Ratio ( $F_t$ ) as a Function of Actual Weight ( $x$ ).

Through systematic data analysis and preprocessing, it was identified that the corresponding data points when  $FT < 0.15$  accounted for approximately 81.5% of the complete dataset. When implementing automated declaration protocols based on these analytical outcomes under risk control alert triggering conditions that  $FT < 0.15$ , a 93% successful clearance rate was achieved. From the perspective of container operation scenarios, values at  $x = 2.3$  and 4 tons (as Fig.1) correspond to empty containers of distinct dimensions (20ft and 40ft, respectively), whereas other values represent loaded container configurations.

#### 4. Theoretical Analysis of System Stability

Following the completion of weight measurement error testing, we proceed to analyze the stability of the gate system by introducing principles from dynamics theory. Drawing upon physical system analogies, the gate system is conceptualized as a complex dynamical system, where the total cargo throughput is treated as the amplitude of the system. In accordance with dynamics theory, this amplitude is modeled as a superposition of vibrational modes governed by Equation (5):

$$W = \sum_{i=1}^N A_{0i} + A_i \cos(\omega_i t + \psi_i), \quad (5)$$

where,  $A_{0i}$  denotes the equilibrium constant,  $A_i$  represents amplitude,  $\omega_i$  is vibrational frequency,  $\psi_i$  represents initial phase,  $t$  is time. In our theory,  $N$  is taken as 3. We depict the time-dependent oscillatory curve of the total cargo weight amplitude processed by the gate system, revealing the dynamic characteristics of the system under operational stresses, as shown in Figure 4.

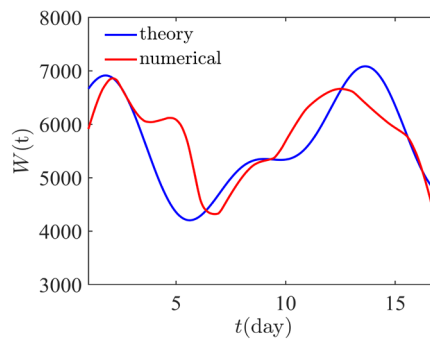


Figure 4. The time-dependent oscillatory curve of the total cargo weight amplitude.

As illustrated in Figure 4, the red curve represents the temporal variation of actual cargo weights processed by the gate system, while the blue curve depicts the theoretically predicted oscillatory behavior of the system's throughput over time. The results demonstrate remarkable agreement between theoretical predictions and empirical observations, confirming that the time-dependent oscillatory patterns of cargo weights in gate operations can be analogized to the dynamic responses of complex mechanical systems. According to phase-space stability theory, the stability of the gate system correlates with the fixed points of the derivative of its amplitude function [6]. The derived function, which governs these stability characteristics, is presented in Figure 5.

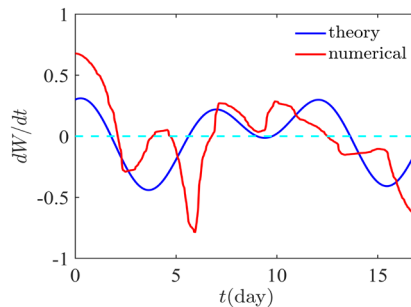


Figure 5. Temporal Evolution of the Phase-Space Function.

Obviously, the derivative function exhibits five fixed points, three of which are identified as stable nodes through Lyapunov stability criteria. Then we get the Lyapunov exponent by Equation (6):

$$\lambda = \lim_{t \rightarrow \infty} \frac{1}{t} \ln \left| \frac{dW}{dt} \right|. \quad (6)$$

According Eq.(6), we obtain the oscillatory curve of the Lyapunov exponent, as shown in Figure 6.

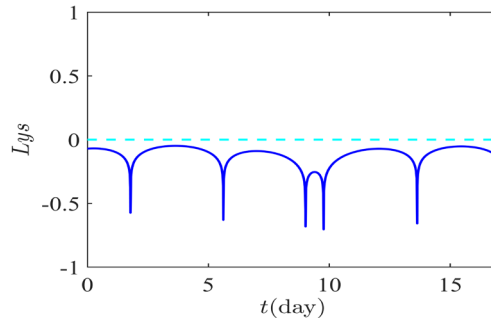


Figure 6. The oscillatory curve of the Lyapunov exponent over time.

In summary, by employing dynamical systems theory and nonlinear dynamics principles, we have successfully predicted cargo weight flow patterns in the gate system and conducted comprehensive stability analyses. The results demonstrate that the gate system exhibits Lyapunov stability characteristics, confirming asymptotic stability under operational perturbations.

## 5. Discussion and Challenges

This study conducted comprehensive analyses on weight datasets from three gate systems: container, roll-on/roll-off (Ro-Ro) cargo, and breakbulk cargo operations. Using the container gate system as a representative case, we implemented an automated weight measurement error testing framework and performed systematic stability analyses. However, the Ro-Ro and breakbulk cargo datasets exhibited significantly higher entropy and multimodal distribution complexities, which were not addressed in the current research scope. Fundamentally, this discrepancy arises from stringent container weight management protocols, whereas weight constraints for Ro-Ro and breakbulk cargo remain loosely defined in this port's operational paradigm.

Additionally, our algorithmic implementation for container gate data processing and modeling demonstrated non-negligible inaccuracies, suggesting three key areas for refinement. Firstly, Multimodal Data Fusion: Integrating container ID verification with weight measurements to resolve tare/gross weight ambiguities. Secondly, Dynamic Thresholding: Adapting LOF parameters to time-varying cargo flow patterns. Eventually, Sensor Calibration: Addressing systematic biases in weighbridge instrumentation.

## 6. Conclusion

In this paper, we focus on the gate systems of different business modes in a certain port. Firstly, the Local Outlier Factor (LOF) algorithm is used to conduct a deep analysis of the recorded weight dataset. Then, taking the container plate gate system as an example, we conducted an automated test for weight error. Finally, we established a flow model by applying the dynamics theory in physics, which predicted the change of the flow at the checkpoint over time relatively accurately, and analyzed the stability of the container gate system by using the Lyapunov stability criteria.

In the future, the volume of port business will continue to grow. We will optimize the data processing and analysis algorithms to conduct more in-depth exploration and analysis of the stability of the gates under different business scenarios.

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