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A multi-tier linking approach to analyze performance of autonomous vehicle-based storage and retrieval systems

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ABSTRACT

To improve operational flexibility, throughput capacity, and responsiveness in order fulfillment operations, several distribution centers are implementing autonomous vehicle-based storage and retrieval system (AVS/RS) in their high-density storage areas. In such systems, vehicles are self-powered to travel in horizontal directions (x- and y- axes), and use lifts or conveyors for vertical motion (z-axis). In this research, we propose a multi-tier queuing modeling framework for the performance analysis of such vehicle-based warehouse systems. We develop an embedded Markov chain based analysis approach to estimate the first and second moment of inter-departure times from the load-dependent station within a semi-open queuing network. The linking solution approach uses traffic process approximations to analyze the performance of sub-models corresponding to individual tiers (semi-open queues) and the vertical transfer units (open queues). These sub-models are linked to form an integrated queuing network model, which is solved using an iterative algorithm. Performance estimates such as expected transaction cycle times and resource (vehicle and vertical transfer unit) utilization are determined using this algorithm, and can be used to evaluate a variety of design configurations during the conceptualization phase.

1. Introduction and literature review

Autonomous Vehicle-based Storage and Retrieval System (AVS/RS) was introduced during the late 1990s to improve the flexibility and responsiveness in handling unit-loads within a warehouse. Savoye Logistics, a France-based equipment manufacturer, pioneered the development of the AVS/RS (see http://www.savoye.com/en). The main components of an AVS/RS are autonomous vehicles, lifts, and a system of rails in the rack area. Autonomous vehicles provide horizontal movement (x-axis and y-axis) within a tier using rails, and lifts provide vertical movement (z-axis) between tiers. Several variants of AVS/RS have been introduced by Vanderlande Industries and Nedcon, and are practiced to handle both unit-load pallets as well as totes (see Fig. 1a for a view of the multi-tier AVS/RS with a lift channel and multiple pallet storage locations, and Fig. 1b for an autonomous vehicle with pallet ejection mechanism).

The type of AVS/RS can be identified based on the nature of resource pooling. A multi-tier AVS/RS where the vehicles are pooled across the tiers is known as the pooled or tier-to-tier system. In this system, any vehicle can store/retrieve pallet to/from any tier location. In contrast to the tier-to-tier system, the vehicles are captive to a tier in the tier-captive configuration, and the vehicles process storage or retrieval transactions in its designated tier only. Tier-captive AVS/RS can improve the vertical transfer unit's capacity because the vehicles are not transferred between the tiers.

Although AVS/RS offer substantial throughput flexibility, they also involve additional operational complexities due to blocking and bottlenecks among the horizontal and vertical load transfer mechanisms. The objective of this paper is to provide a modeling framework and solution methodology to evaluate the performance of AVS/RS with alternate vertical transfer mechanisms. We describe this methodology and demonstrate its application by analyzing the design tradeoffs for a tier-captive AVS/RS. However, the models can be used to analyze the performance of other variants of AVS/RS. We now review the existing AVS/RS studies in three categories: 1) Performance analysis of single-tier AVS/RS, 2) Performance analysis of multi-tier AVS/RS with pooled (tier-to-tier) vehicles, and 3) Performance analysis of multi-tier AVS/RS with tier-captive vehicles.

Performance analysis of single-tier AVS/RS: In the literature, a few studies analyze the performance measures for a single tier of the

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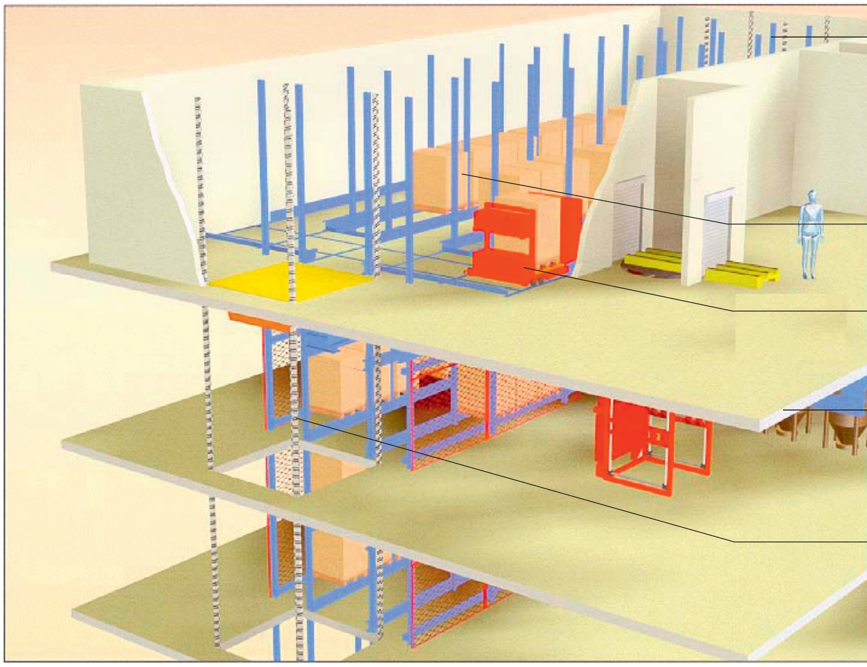
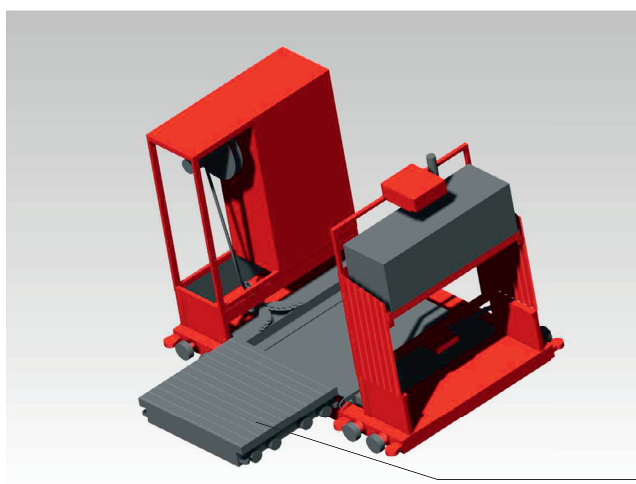


(a)



(b)

Fig. 1. Illustration of (a) a multi-tier AVS/RS with a lift channel and multiple pallet locations, and (b) autonomous vehicle with pallet ejection mechanism (source: Savoye Logistics).

AVS/RS. Roy et al. (2012) develop a semi-open queuing network model to capture the effect of vehicle location, vehicle assignment policies, and number of zones on system performance measures. Roy et al. (2015a) extend the model to analyze alternate dwell-point policy decision and determine the optimal cross-aisle placement decision on system performance measures. The above models do not consider the effect of vehicle blocking. This research gap was addressed by Roy et al. (2014) and Roy et al. (2016), where they developed blocking protocols to capture the additional delays in the aisles and cross-aisles.

Performance analysis of multi-tier AVS/RS with pooled vehicles: There are several studies that analyze multi-tier AVS/RS with pooled vehicles. Malmborg (2002) and Malmborg (2003) develop state-equation models to analyze alternate transaction pairing strategies on system performance. Since solving state equation-based models is computationally expensive, Kuo et al. (2007) presented a computationally efficient nested queuing network model to estimate cycle times where the queuing dynamics between vehicles and transactions is modeled using an $M/G/V$ queue and the dynamics between transactions/vehicles and lift are modeled using a $G/G/L$ queue. Fukunari and Malmborg (2008) and Fukunari and Malmborg (2009) developed a closed queuing network model to account for the time spent outside of the storage rack and to also compare the performance between AS/RS and AVS/RS. However, it lacks the capability for modeling the transaction queuing process. While the earlier models were effective in estimating vehicle utilizations with reasonable accuracy, they were ineffective at estimating transaction waiting times. Therefore, it was difficult to analyze design trade-offs in AVS/RS. Using a series of queuing approximations, Zhang et al. (2009) proposed a procedure for estimating transaction waiting times by dynamically selecting among three alternative queuing approximations based on the variation