Blocking Effects on Performance of Warehouse Systems with Automonous Vehicles

Ananth Krishnamurthy
University of Wisconsin-Madison, ananth.krishnamurthy@wisc.edu

Sunderesh Heragu
University of Louisville

Charles Malmborg
Rensselaer Polytechnic Institute

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Ananth Krishnamurthy, Debjit Roy
Department of Industrial and Systems Engineering,
University of Wisconsin-Madison, Madison, WI-53706, USA

Sunderesh Heragu
Department of Industrial Engineering,
University of Louisville, Louisville, KY-40292, USA

Charles Malmborg
Department of Decision Sciences and Engineering Systems,
Rensselaer Polytechnic Institute, Troy, NY-12180, USA

Abstract

Distribution centers are under increasing pressure to adopt material handling systems that offer greater flexibility to improve cycle time and throughput capacity in the transfer of unit loads in their high density storage areas. Autonomous Vehicles-based Storage and Retrieval Systems (AVS/RS), have been shown to hold significant promise in this context. In these systems, loads are transferred by autonomous vehicles. Vehicles support horizontal load movement along aisles and cross-aisles within a tier, and lifts support vertical movement between tiers. Existing research in AVS/RS, do not explicitly account for the potential blocking of vehicles and lifts while they are processing transactions. Blocking could occur when multiple vehicles use the same cross-aisle or aisle to process transactions. These blocking delays could significantly impact throughput capacity and cycle times. In this research, protocols are developed to address vehicle blocking and a simulation model is proposed to analyze system performance and quantify the effect of blocking.

1. Introduction

Warehouse automation is going to be a key driver for logistics service providers to remain competitive in the future. Distribution centers are embracing automation technologies to enhance the flexibility and responsiveness in varying demand environment. Many distribution centers are exploring autonomous vehicle-based storage and retrieval (AVS/R) technology based solutions to address market needs. This technology offers flexibility in warehouse operations because throughput capacity can be varied by varying the number of vehicles in the system.

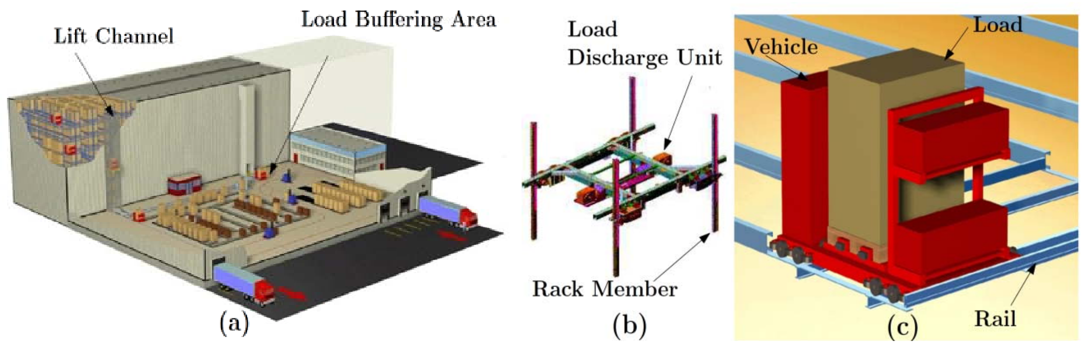

Figure 1: Illustration of: (a) a Warehouse Using AVS/RS - System View, (b) Lift Mechanism, and (c) Vehicle.

The main components of an AVS/RS are autonomous vehicles, lifts, and a system of rails in the rack area (Figure 1). Autonomous vehicles provide horizontal movement (x and y-axis) within a tier using rails and lifts provide vertical movement (z-axis) between tiers. The high-density storage area is composed of several tiers. A tier of the storage area is composed of a set of aisles with storage racks on both side of each aisle and a cross-aisle that runs orthogonal to the aisles. A vehicle travels between aisles using the cross-aisle rail (Figure 2). Autonomous vehicles transport pallets between lifts using tiers.

Two important performance measures of an AVS/RS are throughput (the number of transactions served per unit of time) and transaction cycle times (the time from when a transaction arrives until the time the transaction is processed). These performance measures are influenced by system sizing decisions as well as operational decisions. System sizing decisions typically relate to the tier configuration parameters and operational decisions. Tier configuration parameters include depth/width (*D/W*) ratio, number of vehicles and lifts, location of the cross-aisle, number of zones, and location of load/unload points. The operational decisions include vehicle assignment rule, type of command cycle, transaction scheduling policy, storage policy and choice of dwell points. Transaction cycle time consists of several components such as waiting time for vehicles and lifts, horizontal and vertical travel times, load/unload times, and vehicle blocking delays.

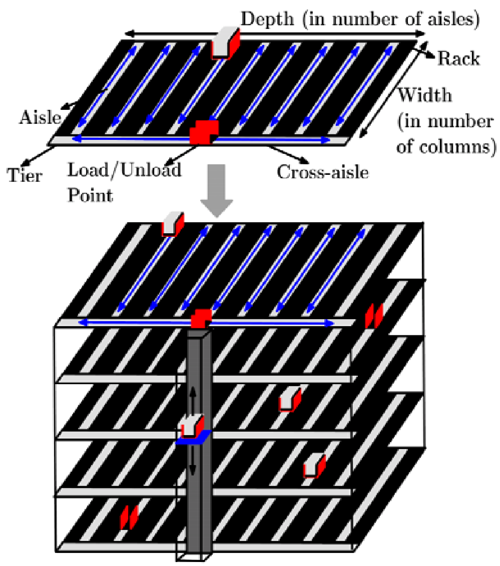

Figure 2: Illustration of a Multi-tier AVS/RS Using a Wireframe Model.

Several analytical models have been developed to aid design engineers during the conceptualization stage of the system and to determine the impact of design parameters on throughput capacity and cycle times for storage and retrieval transactions (Malmborg [1], Kuo et al. [2], Fukunari and Malmborg [3], Roy et al. [4]). Ekren et al. [5] developed a simulation model to identify the design parameters that influence the performance of AVS/RS. However, these models do not explicitly model the potential interference of vehicles and lifts while they are processing transactions. Vehicle interference or blocking could occur when multiple vehicles use the same cross-aisle or aisle to process transactions. When vehicles are blocked, they must wait till the path to the destination location is cleared. These blocking delays could significantly impact throughput capacity and cycle times. This research attempts to investigate the effect of blocking on AVS/R system performance. As a first step, the scope of this research is restricted to a single tier of a high-density storage area.

In AVS/RS, vehicle blocking within a tier can occur at three locations: 1) within a cross-aisle, 2) within an aisle, and 3) at the intersection of an aisle and cross-aisle. Figure 3 presents a 2D layout of tiers with varying *D/W* ratio. Layout 1 corresponds to $D/W>1$ (long cross-aisle and short aisles), whereas layout 2 corresponds to $D/W<1$ (short cross-aisle and long aisles). Though both layouts provide same storage area and operate with five vehicles, the effect of blocking in an aisle may be more pronounced in layout 2 than layout 1. Due to longer length of aisles in layout 2, the chance of a simultaneous access of an aisle by more than one number of vehicles at any point in time is higher. In contrast in layout 1, due to longer cross-aisle, the chance of a simultaneous access of a cross-aisle by more than one number of vehicles at any point in time is higher. Therefore, an understanding of the effect of blocking on throughput and cycle times will help the warehouse design engineers to plan AVS/R systems.

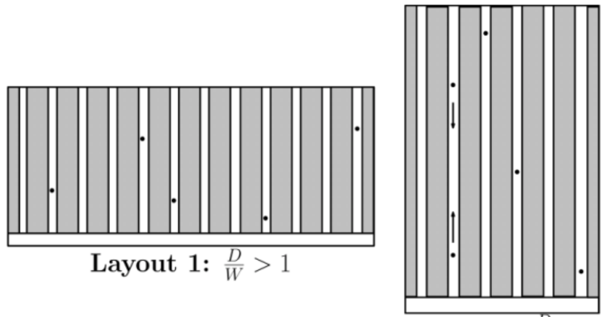

Figure 3: Illustrating Vehicle Blocking in Two Different Layouts of a Tier.

In literature, vehicle collision prevention strategies have been discussed in reference to the design and control of AGV systems. The strategies include, use of a better routing algorithm, use of segmented flow topology (SFT) configurations; identification of imminent collision through forward sensing and consequently avoiding this through vehicle backtracking and/or rerouting; imposing zone control, extensive route pre-planning, and scheduling vehicles based on the time windows. A comprehensive review of these strategies can be found in Le-Anh and De Koster [6]. These strategies assume one or several conditions such as unidirectional path, one vehicle per zone, static routing and scheduling disciplines. In AVS/RS, these strategies do not apply due to bi-directional guide-paths, multiple vehicles per zone, and Poisson transaction arrivals.

Bi-directional guide-paths (aisle and cross-aisle rails) in AVS/RS can cause potential vehicle blocking. Blocking protocols are first developed to assign priorities for usage of aisles and cross-aisles. To evaluate system performance, a detailed simulation model is developed using AUTOMOD software. The interference effects are studied for systems with varying tier configuration parameters such as *D/W* ratio, number of locations, and number of vehicles. These insights are validated against detailed simulations.

The rest of this article is organized as follows. Section 2 illustrates the types of vehicle blocking and presents the protocols for vehicle blocking. Section 3 describes the assumptions, presents the simulation model, explains the simulation approach and defines the performance measures. Section 4 presents the design of experiments and model insights. Conclusions and extensions are discussed in Section 5.

2. Protocols for Vehicle Blocking

In this research, a set of protocols is developed to address the three types of vehicle interference identified earlier (Figure 4). These protocols are described as follows:

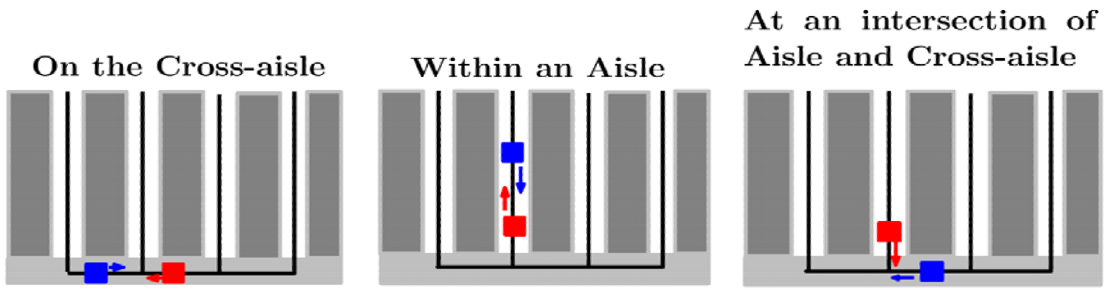

Figure 4: Types of Vehicle Blocking.

Cross-aisle protocol: Vehicles travel from Load/Unload (LU) point to an aisle using the cross-aisle rail and return to the LU point after processing the transaction. Therefore, vehicles access the cross-aisle segment twice during processing a transaction and returning to the dwell point (LU point). To access the cross-aisle, vehicles wait either at the LU point or at the end of an aisle (EOA). If multiple vehicles are waiting at the LU point and EOA to use the cross-aisle simultaneously, blocking on the cross-aisle is modeled by using a simple switching protocol for cross-aisle usage. Vehicles at LU point and at EOA get alternate use of the cross-aisle; and the cross-aisle is seized by vehicles traveling from the LU point (EOA) to the storage/retrieval aisles (LU point) till all the vehicles complete their travel along the cross-aisle. Note that this protocol permits simultaneous usage of the cross-aisle by multiple vehicles, as long as they are all traveling in the same direction on the cross-aisle.

Aisle protocol: A vehicle servicing a transaction within an aisle yields to other incoming vehicles. It is assumed that the former vehicle retreats to the last available bay location and waits until the latter vehicle completes its Load/Unload operation. It is possible that the latter vehicle leaves the aisle and former vehicle is interrupted again by another vehicle. In this case, the former vehicle again retreats to the last bay location and waits until this vehicle completes its Load/Unload operation. Vehicle blocking is modeled within an aisle using this protocol.

Intersection protocol: Vehicles could be blocked at the intersection of an aisle and cross-aisle if one vehicle waits at the EOA to access the cross-aisle and another vehicle attempts to enter the same aisle occupied by this vehicle. To model this situation, after completing service within an aisle, vehicles leave the aisle and wait at a location in front of a rack to access the cross-aisle.

3. Model Description

A detailed simulation model is built to understand the effect of blocking on system performance and analyze the effects of tier configuration parameters on blocking delays. This section includes a description of the model assumptions, system representation, simulation methodology, and performance measures.

3.1 Assumptions

The first set of assumptions is related to configuration of the tier for the simulation model. The LU point is located at the middle of the cross-aisle (Figure 2). In other words, the LU point divides the cross-aisle into two equal segments (CA_R and CA_L: corresponding to the right and left segment of the cross-aisle). Vehicles dwell at the LU point after processing transactions. After a vehicle completes a storage transaction, it travels to the LU point to serve the next transaction. Vehicles process transactions in a single command cycle.

The second set of assumptions pertains to the simulation model. The storage and retrieval transaction arrivals follow a Poisson process with rates λ_s and λ_r respectively. These transactions are served with an FCFS scheduling discipline. Vehicles travel with a constant horizontal travel velocity and acceleration/deceleration effects are ignored. It is assumed that a random storage policy is used, i.e., the storage and retrieval locations are uniformly distributed within the tier. Further, the vehicle assignment rule is random i.e., any idle vehicle is equally likely to be chosen to process a transaction.

3.2 Model of the AVS/RS

The simulation model for the single tier is build using AutoMod© software [7]. The modeling effort consists of two components. The first component of the model building phase is representing the system, whereas the second component is developing the model logic. The model logic controls the allocation of resources and movement of the vehicles in the system.

The tier is modeled using a path mover system. The locations on the path designate LU point, bay locations, cross-aisle wait and aisle yield locations. Storage locations on each side of an aisle are grouped into bays. Each bay consists of three storage locations. Based on the aisle protocol, a vehicle in the aisle yields to other incoming vehicles. The former vehicle backtracks and waits at the last storage (yield) location. Based on the cross-aisle protocol, after completing service within an aisle, a vehicle waits at a location in front of the rack. The locations serve as start and end points for a vehicle travel. The vehicles, which travel in the tier processing storage and retrieval transactions, are modeled as resources. The transactions are modeled as loads, which are of two types - storage and retrieval.

The model logic controls the allocation of resources, movement of the vehicles in the system, and the interaction between vehicles and transactions in a single tier. A transaction arrives and waits in an order list (transaction queue) if it does not find an idle vehicle. Similarly, a vehicles dwells (idles) at the load/unload (LU) point if there are no transactions waiting in an order list. Hence, a transaction could wait for an idle vehicle or a vehicle could wait for a transaction arrival. When both vehicle and transaction are present in the system then a transaction gets matched to a vehicle. Once a transaction claims an idle vehicle, the vehicle travels in the horizontal axes along a rectilinear path and processes the transaction. A detailed simulation flowchart is presented in Figure 5. About 10% of the random storage locations are initialized to a filled with pallet status at the beginning of the simulation run.

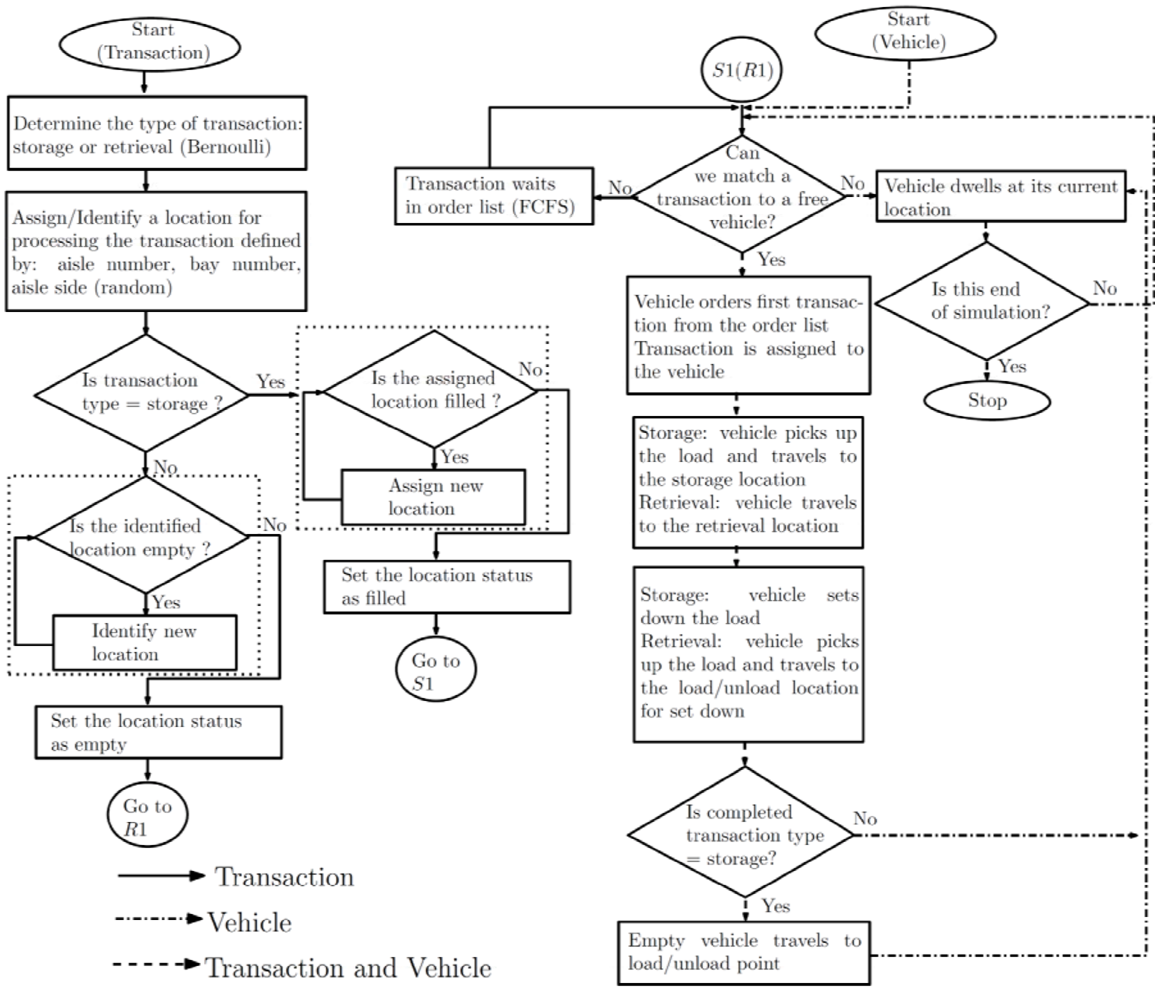

Figure 5: Detailed Simulation Flowchart.

3.3 Performance Measures

The performance measures of interest are transaction cycle times, vehicle utilization, average number of transactions waiting to access a free vehicle, blocking delays at the aisle and the cross-aisles. Table 1 defines the notations used in describing the transaction cycle time components and blocking delays.

Table 1: Notations for the Terms Used in Describing Cycle Time Components.

Notation	Description
CT(s), CT(r)	Cycle time to complete storage and retrieval transaction
W_v	Waiting time to access a free vehicle
W_{clu}	Waiting time to access the cross-aisle from the LU point
W_{crk}	Waiting time to access the cross-aisle from the end of aisle
W_{ar}	Waiting time due to blocking within an aisle (retrieval)
W_{as}	Waiting time due to blocking within an aisle (storage)
v_l	Horizontal travel velocity of a vehicle
x_{lu},y_{lu}	x and y coordinates of the LU point
$(x_r,y_r),(x_s,y_s)$	Coordinates of x and y axes for retrieval and storage location
L_t,U_t	Load and unload time

The total cycle time for retrieval and storage transactions can be expressed as follows:

$$CT(r) = W_v + W_{clu} + \left|\frac{X_{lu}-X_r}{v_l}\right| + \left|\frac{Y_{lu}-Y_r}{v_l}\right| + L_t + W_{ar} + \left|\frac{Y_r-Y_{lu}}{v_l}\right| + W_{crk} + \left|\frac{X_{lu}-X_r}{v_l}\right| + U_t \quad (1)$$

$$CT(s) = W_v + L_t + W_{clu} + \left|\frac{X_{lu}-X_s}{v_l}\right| + W_{as} + \left|\frac{Y_{lu}-Y_s}{v_l}\right| + U_t \quad (2)$$

When a vehicle is processing a storage transaction, the percentage of blocking delay at the aisles, cross-aisles, and overall can be obtained from the formula $W_{as}/CT(s)$, $W_{clu}/CT(s)$, and $(W_{as}+W_{clu})/CT(s)$. Similarly, when a vehicle is processing a retrieval transaction, the percentage of blocking delay at the aisles, cross-aisles, and overall can be obtained from the formula $W_{ar}/CT(r)$, $(W_{clu}+W_{crk})/CT(r)$, and $(W_{clu}+W_{ar}+W_{crk})/CT(r)$.

4. Insights from Simulation Model

To obtain insights on the effects of blocking, a tier configuration with 15000 storage locations, 10 vehicles, and *D/W* ratio of 1.5 is considered. For this configuration, the transaction arrival rates are varied and its impact on average cycle times, utilizations, average number of transactions waiting, and blocking delays are considered. The transaction rate is varied from 108 pallets/hr to 143 pallets/hr at increments of 7 pallets/hr. The utilization levels are studied between 60% and 90%. For each scenario, 15 replications are run with a warm-up period of at least 5,000 transactions and a run time of at least 30,000 transactions. Performance measures are obtained within 95% confidence level and the half-width of a confidence interval is less than 2% of the average. In this research, the insights are focused on the effect of design parameters on blocking delays.

From the model runs, the overall percentage of blocking delays varies from 17% to 21%. Further, storage and retrieval cycle time components are studied to get an insight into the interference delay times. As discussed earlier, delays due to blocking could occur at the cross-aisle or within the aisles. The different components of a storage cycle time in a chronological sequence are wait for vehicle, load pallet, blocking delay at the cross-aisle, travel on cross-aisle, blocking delay within the aisle, travel on aisle, and unload pallet. Similarly, the different components of a retrieval cycle time in a chronological sequence are wait for vehicle, blocking delay at the cross-aisle, travel on cross-aisle, blocking delay within the aisle, travel on aisle, load pallet, blocking delay at the cross-aisle, travel on cross-aisle, and unload pallet.

Figure 6 presents the cycle time components for the tier with 15000 locations, 10 vehicles, *D/W*=1.5, and $\lambda_s=\lambda_r$=68 pallets/hr. In this scenario, the number of vehicles is 10 and the number of aisles is 64. The blocking delays at the cross-aisles are 14.1% and 18.1% for storage and retrieval transactions respectively, whereas the blocking delays at the aisles are 1.6% and 1.8% for storage and retrieval transactions respectively. Clearly, the blocking delays at the cross-aisles appear to be more significant than the blocking delays within the aisles. Blocking delay within an aisle depends on the number of vehicles interrupting a vehicle in an aisle during its service. Interference delay on the cross-aisle depends on the length of cross-aisle segment and the number of vehicles waiting to access the cross-aisle. In this scenario, the number of vehicles is 10 and the number of aisles is 64. So it is less likely that a vehicle in an aisle will be interrupted during its service.

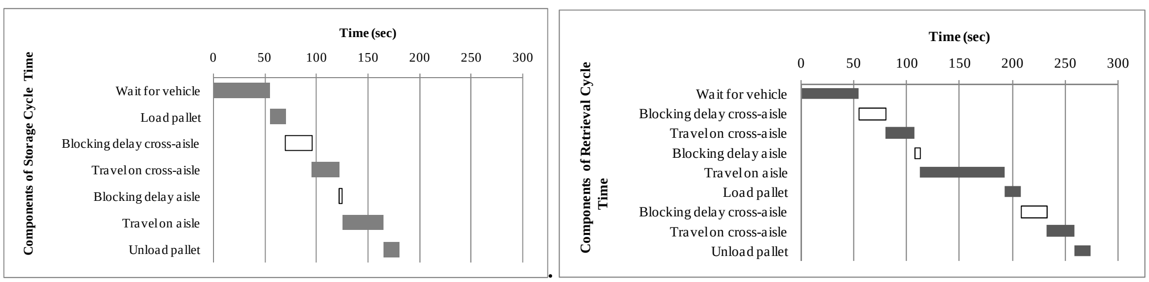

Figure 6: Components of Storage and Retrieval Cycle Times for a Tier with 15,000 Locations, *D/W*=1.5, 10 Vehicles, $\lambda_s=\lambda_r$=68 Pallets/hr

5. Conclusions and Extensions

This research is an initial attempt to model vehicle interference phenomenon in AVS/R systems. Efficient interference protocols are developed to model the system. The simulation model captures the delays due to blocking at the cross-aisle and aisles. Initial studies indicate that blocking delays contribute a significant amount (17%-21%) to the transaction cycle time. Additional studies are needed to investigate the blocking effects of design parameters such as number of vehicles, vehicle utilization, number of storage locations, and *D/W* ratio. Extension of this model to multi-tier systems is a part of ongoing research.

Acknowledgements

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