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Guideline /

Cycle time calculation for automated vehicle storage and retrieval systems

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1 Scope

The term *automated vehicle storage and retrieval systems* is used for storage systems for storing transportation units (TUs) such as containers, boxes or trays. These solutions are increasingly used to supply picking areas based on the *goods to person* principle and to store TUs for high dynamic buffers, for low-access applications and other cases.

The technology is characterized by horizontal transport and vertical transport being largely separated from each other. Usually, the shuttle vehicles perform horizontal transport functions as well as picking up and discharging loads while the vertical transport is realised using lifts.

In the course of further developments, various concepts for system, vehicle, energy and drive have evolved, requiring a holistic consideration in order to determine a concept that lends itself for a specific case of application.

The following systems are not covered in the present guideline and thus are not considered as automated vehicle storage and retrieval systems:

- conventional automated small parts storage systems (ASPSS) with storage and retrieval machines (SRM) conforming with EN 528 and thus “[including] any kind of storage and retrieval machines that are rail-mounted within and outside of the rack aisle, are equipped with a lifting device and that may be equipped with a side-shift device […]”,
- tower storage/lift systems for storing goods on storage trays, sometimes also referred to as a “shuttle” as per the registered wordmark,
- automated guided vehicles (AGV) mainly used for transport,
- transfer carriage systems mainly used for distribution outside of the storage system.

2 Terms and Definitions

For the purposes of this guideline, the following terms and definitions apply:

Shuttle vehicle

(Horizontal) vehicle belonging to an automated vehicle storage and retrieval system, suitable for storage and retrieval tasks and for transporting unit loads.

Automated vehicle storage and retrieval system

System typically comprising several shuttle vehicles, the rack structure, at least one vertical conveyor (lift), a control and, if necessary, an additional conveying system, fire protection and safety equipment.

Cycle time

Time required for a precisely defined and constantly repeating motion sequence.

Note: This is the sum of the time required for the motion sequences (travel time, load pick-up and discharge) plus any auxiliary time such as switching time, positioning time, IT communication time, electrical loading time etc.

3 Abbreviations and symbols

3.1 Abbreviations

The following abbreviations are used throughout this guideline:

ASPSS	automated small parts storage system, containing a stacker crane
AVSRS	automated vehicle storage and retrieval systems
I-P	in position
LHD	load handling device
O-P	out position
SRM	storage and retrieval machine
TU	transport unit, corresponds to storage unit, unit load, bin, tray box or other

3.2 Symbols

The following symbols are used throughout this guideline:

Symbol	**Designation**
a_x	Shuttle vehicle acceleration (x-direction)
a_y	Lift acceleration (y-direction)
C_x	Transport capacity of shuttle vehicle (number of TU)
C_y	Transport capacity of lift (number of TU)
$d_{1,yS}$	Average travel distance of lift in storage single cycle
$d_{1,yR}$	Average travel distance of lift in retrieval single cycle
$d_{2,y}$	Average travel distance of lift in combined (storage and retrieval) cycle
k_{in}	Index of storage level in the rack
k_{out}	Index of retrieval level in the rack
l_x	Average distance between bin locations in x-direction (= length of rack / number of bin locations)
l_y	Average distance between bin locations in y-direction (= height of rack / number of levels)
$l_{0,x}$	Distance in x-direction between hand-over location and first bin location
$l_{0,IP}$	Distance in y-direction between rack level 1 and I-P (negative value means that I-P is situated below level 1)
$l_{0,OP}$	Distance in y-direction between rack level 1 and O-P (negative value means that O-P is situated below level 1)
$m_{L,C}$	Number of lift movements within one double cycle: it is 3 if $l_{0,IP} = l_{0,OP}$ and otherwise 4
$m_{L,Cy}$	Maximum number of lift movements within a combined cycle at a transport capacity of C_y. If $l_{0,IP} = l_{0,OP}$ then $m_{L,Cy} = 2 \cdot C_y + 1$ otherwise $m_{L,Cy} = 2 \cdot C_y + 2$.
n_L	Number of lifts or pairs of lifts
$n_{Shuttle}$	Number of shuttle vehicles
n_x	Number of bin locations in longitudinal direction (x-direction)
n_y	Number of levels in the storage system (y-direction)

$n_{x,rel}$	Average number of bins to the next free one in case of relocation (x-direction)
p_x	Probability of approaching a bin location in a given level of the rack
p_y	Probability of approaching a level in the rack
$t_{C1,x}$	Average cycle time for a single cycle of shuttle vehicle
$t_{C1,xS}$	Average cycle time for a storage single cycle of shuttle vehicle
$t_{C1,xR}$	Average cycle time for a retrieval single cycle of shuttle vehicle
$t_{C1,y}$	Average cycle time for a single cycle of lift
$t_{C1,yS}$	Average cycle time for a storage single cycle of lift
$t_{C1,yR}$	Average cycle time for a retrieval single cycle of lift
$t_{C2,x}$	Average cycle time for a double cycle of shuttle vehicle
$t_{C2,y}$	Average cycle time for a double cycle of lift
$t_{CC,y}$	Average cycle time for a multiple cycle of lift
$t_{C1,x2S}$	Average cycle time for a storage single cycle of shuttle vehicle and double deep storage
$t_{C1,x2R}$	Average cycle time for a retrieval single cycle of shuttle vehicle and double deep storage
$t_{C2,x2}$	Average cycle time for a double cycle of shuttle vehicle and double deep storage
t_{PD}	General time for pick-up and discharge. If both times are different, the average value should be used.
$t_{PD,z}$	Time taken for the shuttle vehicle to pick up or discharge a TU (loading time for a movement in z-direction). In case of double deep storage a distinction is made between an access in front ($t_{PD,z1}$) or rear bin location ($t_{PD,z2}$)
$t_{PD,xS}$	Time taken for the lift to pick up or discharge a shuttle vehicle (loading time of lift for a movement in x-direction)
$t_{PD,xT}$	Time taken for the lift to pick up or discharge a TU (loading time of lift for a movement in x-direction)
$t_{PD,xC}$	Time taken for the lift to pick up or discharge C_y TUs (simultaneously or sequentially)
$t_{S,x}$	Total time of all switching, positioning and control operations in x-direction (for a single shuttle vehicle movement)
$t_{S,y}$	Total time taken for all switching, positioning and control operations in y-direction (for a single lift vertical movement)
$t_{T1,x}$	Average travel time for an entire single cycle of shuttle vehicle

$t_{T,yR}$	Average travel time of lift between retrieval level in the rack and O-P and back
$t_{T,yS}$	Average travel time of lift between I-P and storage level in the rack and back
$t_{T2,x}$	Average travel time for an entire double cycle of shuttle vehicle
$t_{T2,y}$	Average travel time for an entire double cycle of lift
$t_{TC,y}$	Average travel time for an entire multiple cycle of lift
$t_{T,rel}$	Average travel time for an additional relocation cycle in case of double deep storage
t_W	Waiting time (waiting for lift)
v_x	Maximum travel speed (of shuttle vehicle in x-direction)
v_y	Maximum lifting speed (of lift in y-direction)
λ_x	Number of cycles per hour for the shuttle vehicle
λ_y	Number of cycles per hour for the lift
$\omega_{m,x}$	Probability of changing shuttle position by *m* bin locations within one level
$\omega_{m,y}$	Probability of changing lift position by *m* levels

4 Automated vehicle storage and retrieval system

4.1 System description

Shuttle vehicles usually travel in a horizontal direction (x-direction) in the rack. The LHD of the vehicle takes hold of the TUs in z-direction. The lift carries out movements in y-direction and transports the TUs or the shuttle vehicles from the I-P hand-over location to the storage level or vice versa from the storage level to O-P. Storage and retrieval levels can be identical. The basic design including system axes is shown in Figure 1. The system axes are used as per FEM 9.831:

x – aisle longitudinal direction

y – vertical direction

z – cross-aisle direction

Usually, several shuttle vehicles per warehouse aisle move simultaneously on running rails at different rack levels and can therefore perform storage and retrieval tasks simultaneously and independently of each other.

During a storage action, the TUs are supplied in the pre-storage area at I-P and transported to the relevant storage level by the lift. TUs leave the lift and wait at hand-over location to be moved with shuttle vehicle to the storage location in a horizontal direction.

During a retrieval action, the TUs are picked up by the shuttle vehicle at the storage location and transported to the lift hand-over location in a horizontal direction. The lift then carries out the movement to O-P.

Two basic designs of automated vehicle storage and retrieval systems are distinguished (Figure 2):

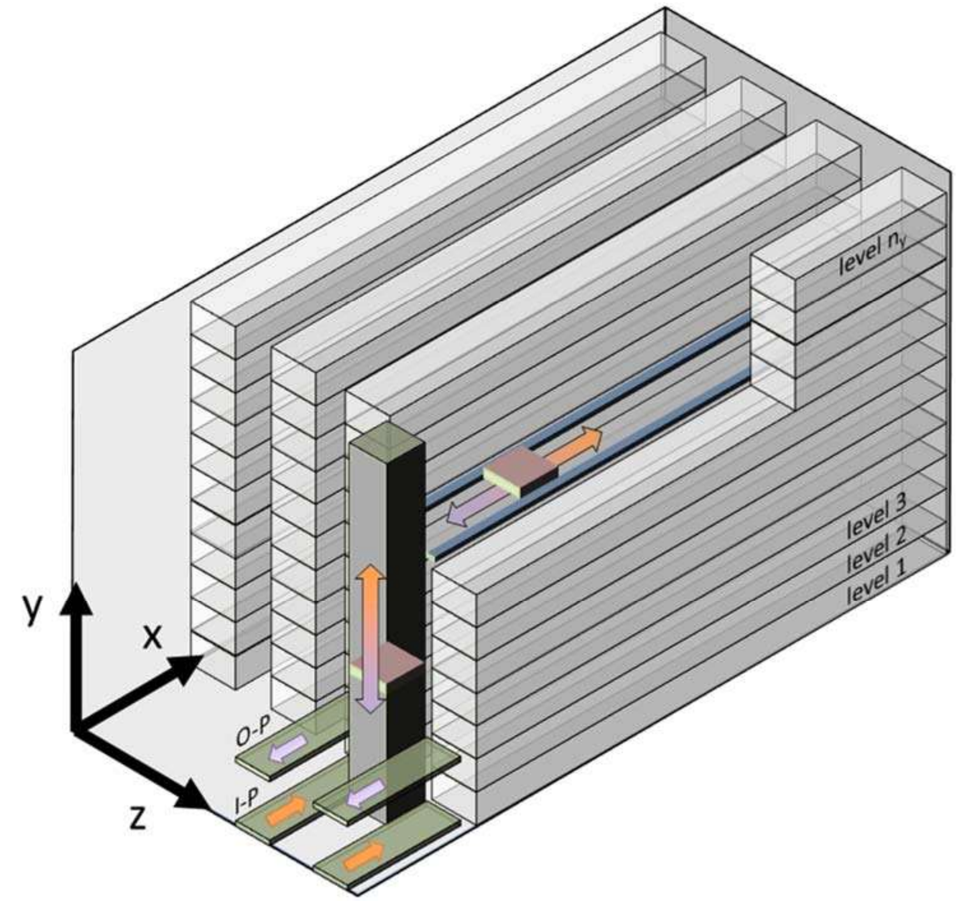

Figure 1: System axes

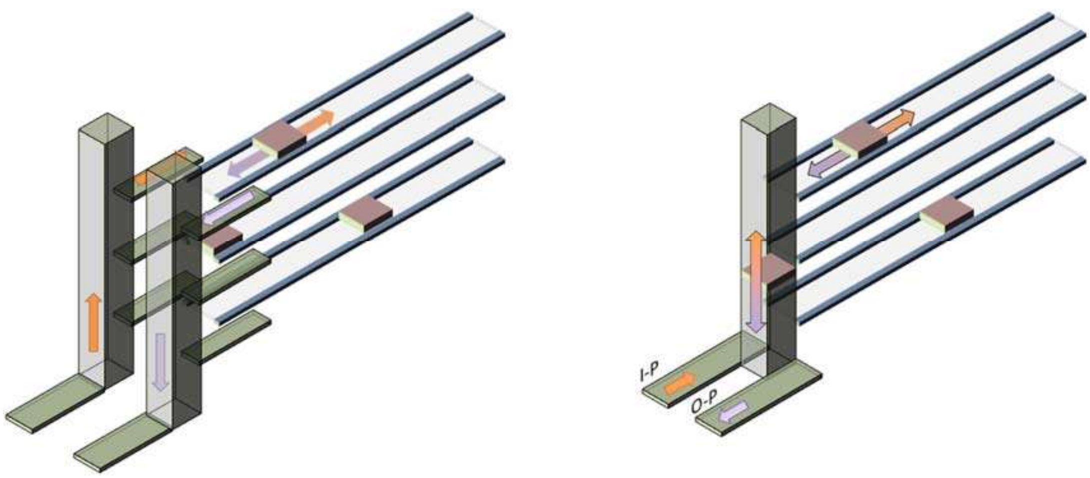

Figure 2: Basic designs of automated vehicle storage and retrieval system: with TU lift (left), with vehicle lift (right)

Systems with **TU lifts** usually consist of one lift or two lifts at the face side of each rack that pick up TUs. If there are two lifts, the directions of load movement can be separated: one lift transports TUs to be stored from I-P to the relevant rack level while the other one transports TUs to be retrieved from rack level to O-P. As an alternative, lifts can perform storage and retrieval tasks in a combined cycle. So-called transfer buffers for the TU are located at every level to decouple the movements of lifts and vehicles. Usually, one shuttle vehicle is used per level. Alternatively, the systems can be equipped with an additional vehicle lift to enable the shuttle vehicles to move between levels. Automated vehicle storage and retrieval systems with TU lifts are suitable for applications with high throughputs (e.g. picking, order consolidation).

Systems with **vehicle lifts** usually consist of a lift at the face side of the rack aisle to pick up an empty shuttle vehicle or a shuttle vehicle carrying a TU. Using this lift, shuttle vehicles can transport TUs to I-P or O-P or can change rack levels. It is not necessary to have a shuttle vehicle per level since these can be moved to the relevant levels in line with demand using the lift. TU pick-up and discharge are performed by the shuttle vehicle LHD. This design meets the requirements of applications with low to medium throughputs and offers a high degree of flexibility. As demands on throughput increase, additional shuttle vehicles can be deployed.

In addition, several variations of these basic designs exist, e.g.:

- Shuttle vehicle and lift with device for handling of multiple loads. This means that several (usually two to four) TUs can be moved simultaneously.
- Shuttle vehicles with swivelling transport wheels or an additional side undercarriage enable deployment in a rectangular transport grid. In this way, shuttle vehicles can also change aisles within the rack system.
- Shuttle vehicles with an additional smaller shuttle vehicle on board which are moved in so-called channels of a channel storage system. While the smaller vehicles transport TUs inside the channels, the larger shuttle vehicles run transversely to the bearing direction and connect the channels with the lift.

4.2 Vehicle concept

Vehicle concepts with a vertically moving load handling device that can serve more than just one storage level are not automated vehicle storage and retrieval systems as defined in this guideline. However, provided the vehicle stroke is small in relation to the aisle length, the performance considerations below can nevertheless be applied to multi-level vehicles.

The vehicle housing contains the entire drive and control equipment as well as energy supply and storage components. A number of sensors support vehicle control, e.g. for position and storage bay occupancy detection, etc.

The shuttle vehicle is a distinctive element of the overall system; however, ultimately it is just one component of the automated vehicle storage and retrieval system and cannot be used without suitable sub-systems.

4.3 Load handling devices

At least one load handling device (LHD) is attached to the shuttle vehicle, that is equipped with the known technologies for ASPSS, e.g. gripping device, telescopic table, belt conveyor, clamping device, pulling device. For this guideline, only the duration of the charging process which depends on the different technologies is relevant, and not the technology itself.

This guideline covers the handling of one TU at a time by the shuttle. In the case that multiple TUs are handled, the calculation can be based on the formulae used with respective adaptations.

4.4 Wheel arrangements/undercarriage concepts

Usually, the shuttle vehicle is rail-mounted and designed for straight line travel. In some systems, directional changes are realized with additional system elements such as swivel wheels, a second set of wheels or additional transfer cars.

Usually, the shuttle vehicles are equipped with four or, in exceptional cases, with three wheels. For transition points or rail gaps, distance dimensions in the range of < 10 mm are therefore required.

In addition, there are shuttle vehicles that can move both lengthways and sideways via rotatable or liftable wheel sets. Here, too, tracking is ensured by the rail.

4.5 Rack system

In the basic version, the rack corresponds to the conventional rack of an ASPSS, i.e. a shelf-based or (angled) rack or, alternatively, a flow-through rack. In this area, the known requirements apply regarding the transfer of static loads from goods to be stored and the storage and retrieval machine; the dynamic loads from storage and retrieval machine acceleration, storage and retrieval service and buffers/end stops if applicable as well as any other loads resulting from supply.

However, there are fundamental differences in comparison to a conventional ASPSS:

- Shuttle vehicles need running rails and, if necessary, energy supply per driving level. In most automated vehicle storage and retrieval systems, these are integrated into the rack.
- Advantageously, the racks are not limited to the rectangular working spaces or surfaces of an SRM. Since the shuttle vehicles of the different storage levels operate independent of each other, storage levels can be designed with different lengths. This means that for the rack structure, any body design is possible.
- Accessible maintenance platforms can be integrated into the rack for maintenance and fault repair purposes.
- Compared to storage systems that are served by an SRM, minimal lower approach dimensions can be achieved. Since no SRM running rails and no SRM travel units are present, the lowermost rack level can be positioned at a very small distance to the floor. This leads to a better degree of volume utilisation.