Designation: ~~F3244 – 17~~ F3244 – 21

Standard Test Method for Navigation: Defined Area[1]

This standard is issued under the fixed designation F3244; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 *Purpose:*

1.1.1 The purpose of this test method is to evaluate an ~~A-unmanned~~ automatic, automated, or autonomous-unmanned ground vehicle's (A-UGV) capability of traversing through a defined space with limited A-UGV clearance. This test method is intended for use by A-UGV manufacturers, installers, and users. This test method defines a set of generic 2D area shapes representative of user applications and for different A-UGV types.

1.1.2 A-UGVs shall possess a certain set of navigation capabilities appropriate to A-UGV ~~operations such as~~ operations. Two examples of such capabilities include A-UGV movement between structures that define the vehicle ~~path.~~ path or obstacle avoidance. A navigation system is the monitoring and controlling functions of the A-UGV, providing frequent A-UGV updates of vehicle movement from one place to another. A-UGV environments often include various constraints to A-UGV ~~mobility.~~ mobility, such as boundaries and obstacles. In this test method, apparatuses, impairments, procedures, tasks, and metrics are specified that apply constraints and thereby, standard test methods for determining an A-UGV's navigation capabilities are defined.

1.1.3 This test method is scalable to provide a range of dimensions to constrain the A-UGV mobility during task performance.

1.1.4 A-UGVs shall be able to handle many types of open and defined area complexities with appropriate precision and accuracy to perform a particular task.

1.1.5 The required mobility capabilities include ~~preprogrammed or autonomous movement or both~~either preprogrammed movement, autonomous movement, or a combination of both, from a start ~~point~~location to an end ~~point.~~location. Further mobility requirements may include: sustained speeds, vehicle reconfiguration to pass through defined spaces, payload, A-UGV movement within constrained volumes, A-UGV avoidance of obstacles while navigating, or other vehicle capabilities, or combinations thereof. This test method is designed such that a candidate A-UGV can be evaluated as to whether ~~or not~~ it meets a set of user application requirements.

1.1.6 This test method is used to evaluate the capabilities of a single A-UGV operating with commands and data provided to it by an operator (for example, locations of goal points, map of the environment), as well as those derived from its own sensors (for example, locations of obstacles in the environment), as opposed to information provided to it from another A-UGV or fleet controller. There may be future standards that address the capabilities of multiple A-UGVs – or fleets – that work together.

1.1.7 This test method does not consider the act of acquiring or removing payloads, such as picking up/dropping off a pallet or connecting to/disconnecting from a trailer, during navigation. The A-UGV may have a payload as part of its configuration (see Practice F3327) that will be unchanged during the test. A future standard may address these types of capabilities during navigation.

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[1] This test method is under the jurisdiction of ASTM Committee F45 on ~~Driverless Automatic Guided Industrial Vehicles~~Robotics, Automation, and Autonomous Systems and is the direct responsibility of Subcommittee F45.02 on Docking and Navigation.

Current edition approved ~~July 1, 2017~~July 1, 2021. Published ~~October 2017~~August 2021. Originally approved in 2017. Last previous edition approved in 2017 as F3244 – 17. DOI: ~~10.1520/F3244-17.~~10.1520/F3244-21.

1.1.8 *Performing Location*—This test method shall be performed in a location where the apparatus and environmental test conditions can be fully implemented. Environmental conditions are specified and ~~recorded.~~recorded (see Practice F3218).

1.1.9 Additional test methods within Committee F45 are anticipated to be developed to address additional or advanced mobility capability ~~requirements.~~requirements, such as a fleet of A-UGVs coordinating their movement through a facility.

1.2 *Units*—The values stated in SI units are to be regarded as the standard. The values given in parentheses are not precise mathematical conversions to inch-pound units. They are close approximate equivalents for the purpose of specifying material dimensions or quantities that are readily available to avoid excessive fabrication costs of test apparatuses while maintaining repeatability and reproducibility of the test method results. These values given in parentheses are provided for information only and are not considered standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. Safety standards such as ANSI/ITSDF B56.5, ~~BS EN 1525,~~ ISO 3691-4:2020, or other safety standards should be followed. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

F3200 Terminology for Driverless Automatic Guided Industrial Vehicles

F3218 Practice for ~~Recording~~Documenting Environmental ~~Effects~~Conditions for Utilization with A-UGV Test Methods

F3243 Practice for Implementing Communications Impairments on A-UGV Systems

F3327 Practice for Recording the A-UGV Test Configuration

F3381 Practice for Describing Stationary Obstacles Utilized within A-UGV Test Methods

F3499 Test Method for Confirming the Docking Performance of A-UGVs

2.2 *ANSI/ITSDF Standard:*[3]

ANSI/ITSDF B56.5 Safety Standard for Driverless, Automatic Guided Industrial Vehicles and Automated Functions of Manned Industrial Vehicles

2.3 *~~BS~~ISO Standard:*[4]

~~BS EN 1525~~ ISO 3691-4:2020 ~~Safety of Industrial Trucks. Driverless Trucks and~~Industrial Trucks - Safety Requirements And Verification - Part 4: Driverless Industrial Trucks And Their Systems

3. Terminology

3.1 *Definitions*—~~In~~ Terminology F3200~~, additional definitions relevant to this test method are given.~~ defines terms that may be used throughout this standard.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *end goal, n*—location at which a task will be completed and is defined by a line perpendicular to vehicle movement.

3.2.2 *goal(s), n*—location(s) the vehicle will pass through as a task is progressed.

3.2.3 *impairment(s), n*—an object, feature, or quality of the situation/environment that is utilized to disrupt intended A-UGV operation, such as the inclusion of obstacles or communication failures during task performance. **F3200**

3.2.3.1 *Discussion*—
For this test method, A-UGV operation refers to the A-UGV navigating from the start to the goal.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] Available from Industrial Truck Standards Development Foundation (ITSDF), 1750 K St. NW, Suite 460, Washington, DC 20006.

[4] Available from ~~British Standards Institution (BSI), 389 Chiswick High Rd., London W4 4AL, U.K., http://www.bsigroup.com.~~International Organization for Standardization (ISO), ISO Central Secretariat, Chemin de Blandonnet 8, CP 401, 1214 Vernier, Geneva, Switzerland, https://www.iso.org.

3.2.4 *intended behavior, n*—A-UGV state or activity, set by the test requestor, that defines success criteria for the completion of a task repetition.

3.2.5 *obstacle, n*—static or moving object or feature that obstructs the intended movement. **F3200**

3.2.6 *obstacle footprint, n*—a rectangular area of space that will be occupied by an obstacle during testing with dimensions matching that of the top-down contour area of the obstacle (that is, its outermost horizontal edges), used to describe the position and orientation of the obstacle in the environment relative to the boundaries.

3.2.6.1 *Discussion*—
See Fig. 1 for examples of obstacle footprints for different types of obstacles.

3.2.7 *start, n*—location at which the A-UGV will begin the test and is defined by a line perpendicular to vehicle movement.

3.2.8 *task, n*—~~see Terminology~~sequence of ~~F3200 definition.~~movements and measurements that comprise one repetition within a test. **F3200**

3.2.8.1 *Discussion*—
For this test method, one task is defined as when the A-UGV moves from the specified start location (Point A) to the goal location (Point B or C), as shown in Figs. ~~1-~~2-~~7~~8, traversing in a specified direction (forward or reverse). Where possible, the A-UGV should return to the start line using autonomous control without operator intervention.

4. Summary of Test Method

4.1 *Area Definition*—This test method consists of traversing multiple repetitions of a single task within a specified navigation area defined by physical barriers, virtual barriers, ~~or~~ floor markings, or combinations thereof. Further details are given in Section 6. Figs. ~~1-~~2-~~7~~8 show possible defined area navigation constraints and references to locations within the apparatus (A, B, and C) and start and goal lines. Using these shapes, the test method can be used to determine an A-UGV's capability at traversing through an area of specified dimensions. The test method could also be used to determine the minimum space in which the A-UGV is able to traverse.

4.2 *Navigation Test Method:*

4.2.1 The A-UGV ~~shall drive~~ drives through the apparatus (examples are shown in Fig. 9 and Fig. 10). The apparatus layout is defined by physical boundaries, virtual boundaries, or floor markings around the area where the A-UGV will drive. Start and goal lines are positioned to define a start location (A) and goal locations (B or C). The completion of one ~~of the repetitions~~ task repetition is when the A-UGV traverses from the ~~specified start location (A) across an end goal line (B or C).~~ start location and its performance satisfies the intended behavior set by the test requestor, which generally is set as crossing the goal line and reaching the goal location without colliding with the environment. If the test requestor selects obstacles or communication impairments to be used in the defined area during navigation, then the intended behavior for the A-UGV may be set to stop and cease navigation once the impairment is encountered. The A-UGV shall not make contact with any ~~barrier~~ boundary or obstacle (unless with only a contact-sensing device that is used to navigate) nor deviate from the defined area during a task. If the A-UGV makes contact with any barrier or crosses a virtual barrier during a repetition, the result is a test failure. The test requestor has the authority to select defined ~~path~~area width(s) (x_a or ~~y,~~y_a, or both, in Figs. ~~1-~~2-~~7~~8) for the ~~test event. The defined path~~test, in addition to several other variables related to the boundaries (for example, height, chamfers) and impairments (for example, obstacle dimensions, position in the apparatus). The defined area width may be altered by the test requestor prior to a test with the aim of identifying the minimum space that can be traversed by the A-UGV, if desired.

~~4.2.2 A task is successfully completed when the entire A-UGV crosses the specified start line at the start location (A), traverses within the defined area, and crosses the specified goal line at the end goal (B or C) without crossing or impacting the physical barriers, virtual barriers, or floor markers.~~

4.2.2 The A-UGV's navigation capability is defined by its ability to repeatedly travel through a defined area ~~from~~ when commanded to traverse from a start to end goal. The test does not require a specific route to be followed by the A-UGV. The route definition is not part of the standard test, nor the line that may be followed, to a certain repeatability. The test is set out to identify the area required for A-UGV movement. This test also does not address the end position of the A-UGV once it is passed the goal line to reach the goal location; see Test Method F3499 test method for docking to evaluate this type of capability for fine positioning.

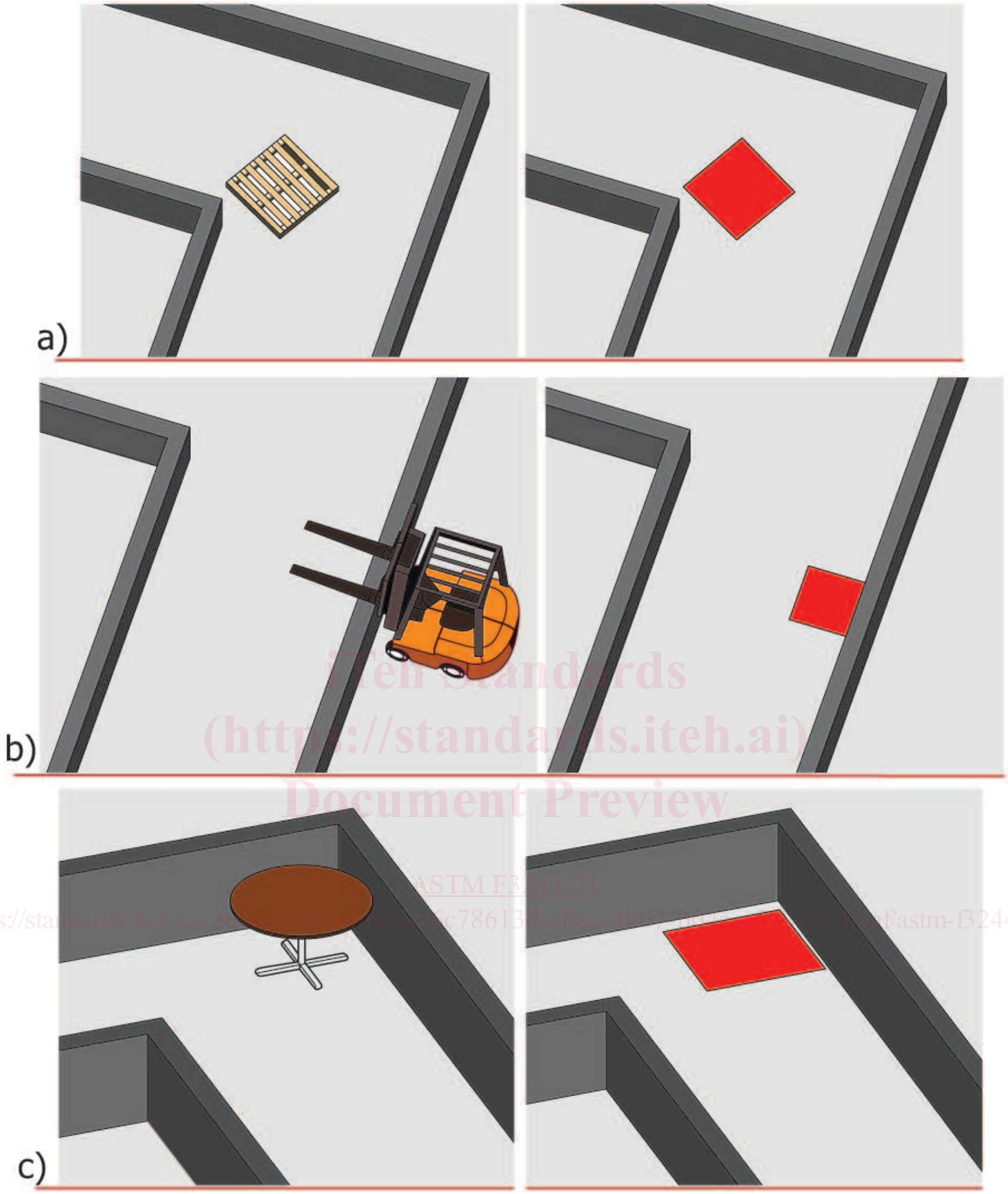
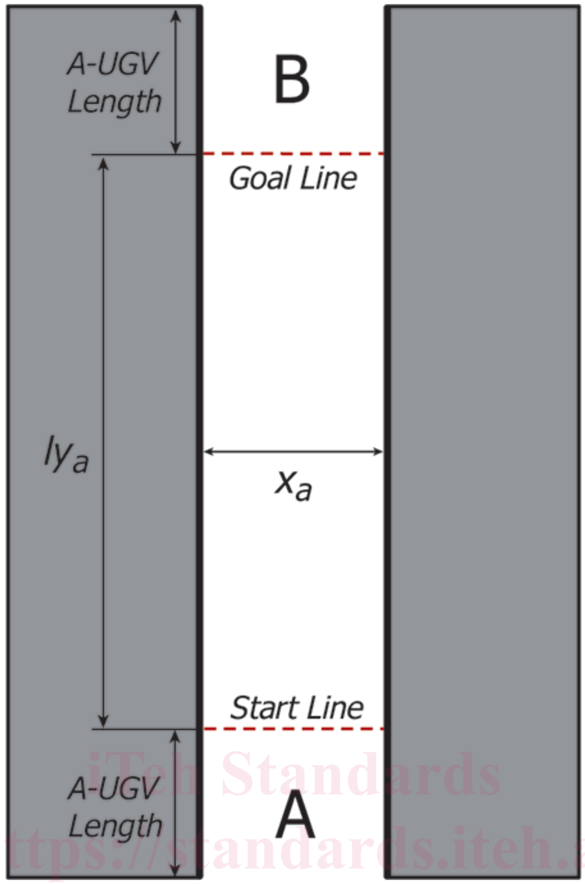


FIG. 1 Examples of Obstacles (left) and Their Corresponding Obstacle Footprints (right) Within a Defined Area Apparatus (a) Pallet (b) Fork Tines (c) Table

4.2.3 The test supervisor will inform the test requestor of the number of task repetitions to be made, corresponding to the statistical reliability and confidence levels shown in Table 1.

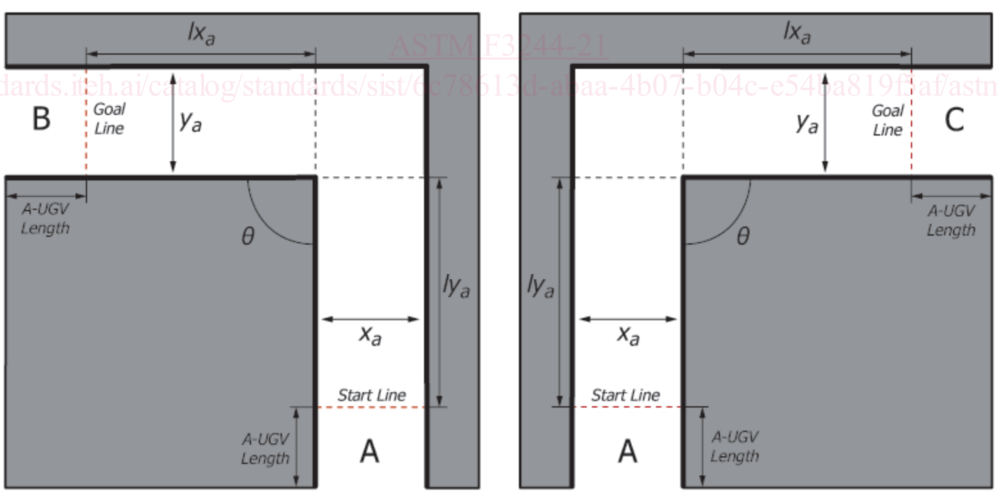
4.2.4 The test supervisor is responsible for setting up the apparatus and instrumentation, directing the test, and reporting results of the test to the test requestor.

4.2.5 The test supervisor will be responsible for directing the test technician and the A-UGV operator.



NOTE 1—The thick black lines indicate the physical barriers or lines along which virtual barriers or floor markings are set.

FIG. ~~1~~2 Diagram of Test Method for Navigation through a Straight Aisle

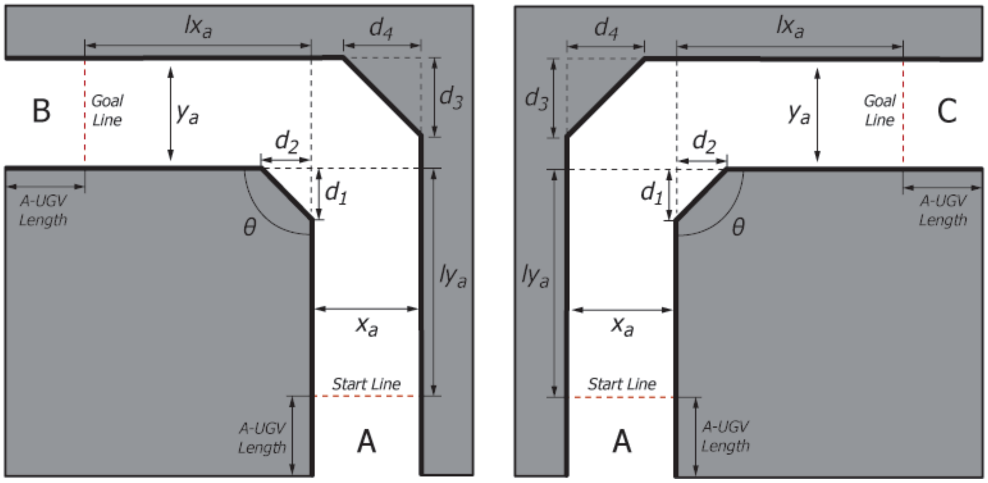


NOTE 1—The thick black lines indicate the physical barriers or lines along which virtual barriers or floor markings are set.

FIG. ~~2~~3 Diagrams of Test Method for Navigation through a Single Intersection with No Chamfers, Showing Both Possible A-UGV Turn Directions

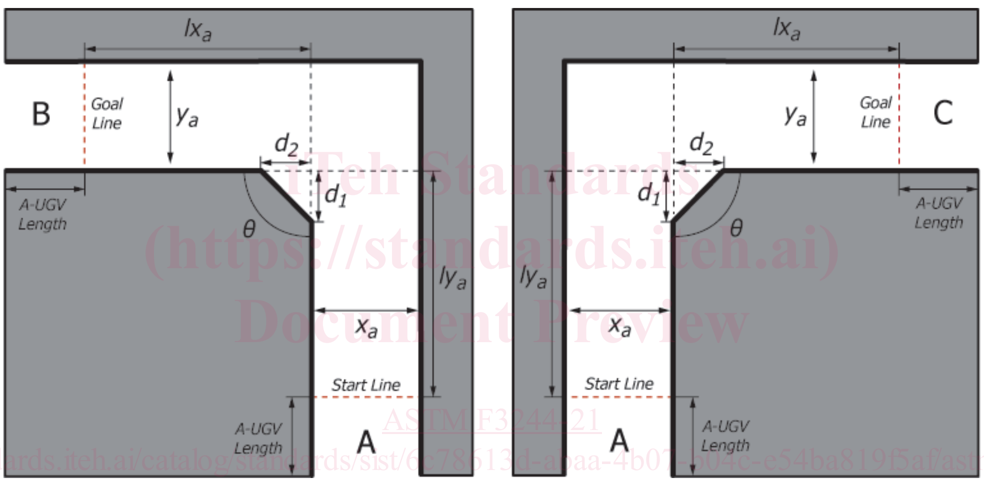
4.3 *Metrics*—~~Derived~~ Partially derived from Figs. ~~1-~~2-~~7~~8. All measurements shown in the figures related to a 2D space with a flat, horizontal floor. Measurements between boundaries are perpendicular to the boundary being measured.

4.3.1 *Straight Aisle Width* (Fig. ~~1~~2)—The value, ~~x,~~ x_a, is the distance between boundaries representing the area needed by the A-UGV to traverse through a straight aisle.



NOTE 1—The thick black lines indicate the physical barriers or lines along which virtual barriers or floor markings are set.

FIG. ~~3~~4 Diagrams of Test Method for Navigation through a Single Intersection, Showing Interior Chamfer Defined by d_1 and d_2 and Exterior Chamfer Defined by d_3 and d_4, Showing Both Possible A-UGV Turn Directions



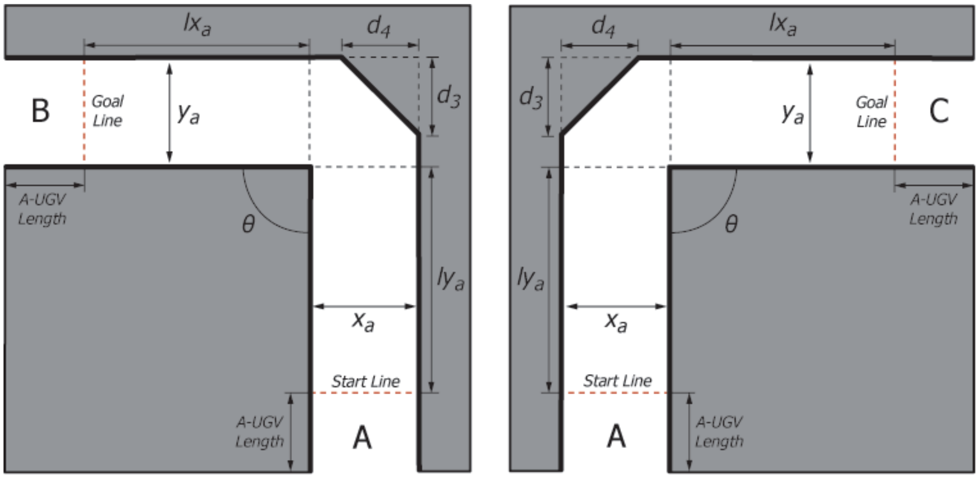
NOTE 1—The thick black lines indicate the physical barriers or lines along which virtual barriers or floor markings are set.

FIG. ~~4~~5 Diagrams of Test Method for Navigation through a Single Intersection with Interior Chamfer Only, Defined by d_1 and d_2, Showing Both Possible A-UGV Turn Directions

4.3.2 *Intersecting Aisles Widths (Single and Dual,* Figs. ~~2~~-3-~~7~~8*)*—The same discussion of aisle width described in 4.3.1 applies here. However, there are two measured widths to be determined: the initial aisle width, ~~x,~~ x_a, and the final aisle width, ~~y.~~ y_a. The combination of these metrics describes the dimensions of traversable 2D space by an A-UGV through an intersection of θ degrees. The default value of θ is 90° for a perpendicular intersection, but angles other than 90° may be selected by the test requestor.

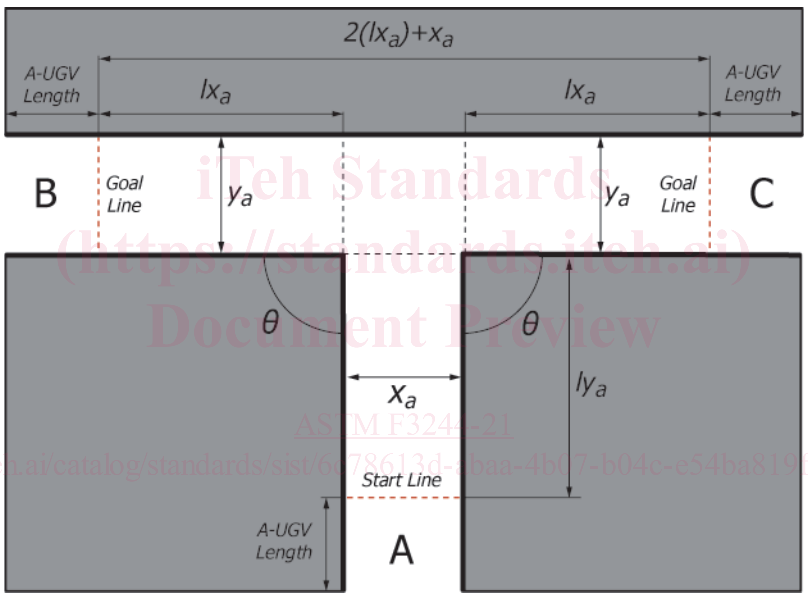
4.3.3 *Chamfered Corners*—These enable the test requestor to further specify the shape of the corners of an area. Chamfers are defined by setback distances for the interior chamfer ~~(d~~(d_1 and d_2) see Fig. ~~4~~5 and the exterior chamfer ~~(d~~(d_3 and d_4), see Fig. ~~5~~6. The setback distance is that distance between the virtual corner and the start of the chamfer identifying the interior space. The interior chamfer enables the width of the aisle intersection to be increased from that identified in the single intersection (see Fig. ~~4~~5) or dual intersection (see Fig. ~~7~~8). The exterior chamfer enables the width of the aisle intersection to be decreased from that identified in the single intersection (see Fig. ~~5~~6). Both interior and exterior chamfers can be used in the single intersection (see Fig. ~~3~~4).

4.3.4 *Obstacle Inclusion*—Obstacles ($o1$,$o2$, etc.) may be included inside of the defined area to impair A-UGV navigation. Practice F3381 can be used to describe the characteristics of the obstacles used. The locations and orientations of the obstacle footprints are recorded ($|x_{o1}|$, $|y_{o1}|$, θ_{o1}, $|x_{o2}|$, $|y_{o2}|$, θ_{o2}, etc.) with respect to an obstacle origin point (p_{o1},p_{o2}, etc.) and a boundary in the apparatus (see Fig. 10). There is no limit on the number of obstacles that can be included. Obstacles may be positioned in such a way that the A-UGV is not able to reach the goal, which would require that the intended behavior be set accordingly (see 4.3.8).



NOTE 1—The thick black lines indicate the physical barriers or lines along which virtual barriers or floor markings are set.

FIG. ~~5~~6 Diagram of Test Method for Navigation through a Single Intersection with Exterior Chamfer Only, Defined by d_3 and d_4, Showing Both Possible A-UGV Turn Directions



NOTE 1—The thick black lines indicate the physical barriers or lines along which virtual barriers or floor markings are set.

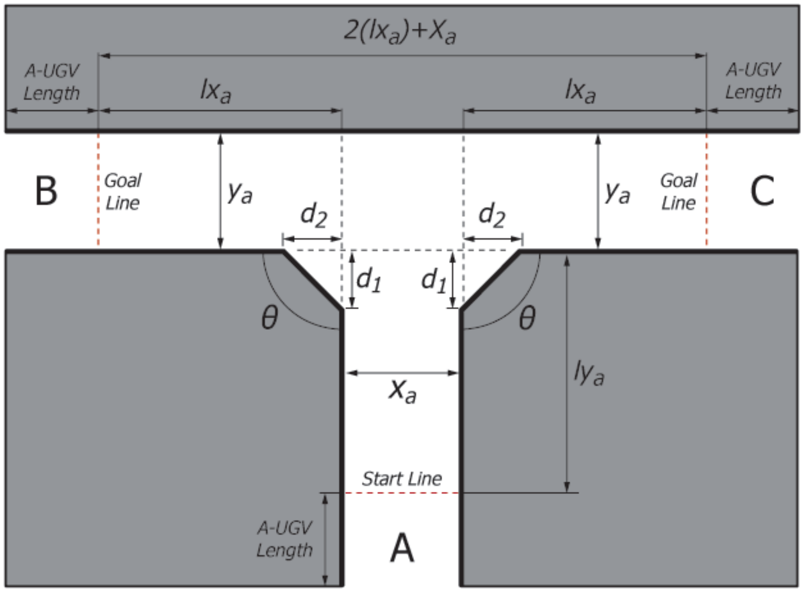
FIG. ~~6~~7 Diagram of Test Method for Navigation through a Dual Intersection with No Chamfers

4.3.4.1 *Dynamic/Moving Objects*—A future standard will provide the means to describe a moving object, similar to what is done for stationary obstacles in Practice F3381. It is expected that this standard test method will later be revised to accommodate to inclusion of moving objects as obstacles, such as defining the start and end location of the obstacle's trajectory as it moves in the defined area.

4.3.5 *Completion Time*—The start time of a task is considered the moment the entire body of the A-UGV crosses the start line, exiting the start location (A). The end time of a task is considered the moment the entire body of the A-UGV crosses the goal line entering the end goal location (B or C) (see Figs. ~~1–~~2–~~7~~8). Task completion time is recorded to an accuracy of 1 s for each repetition, and test completion time is recorded as an average of all completed task repetitions.

4.3.6 *Path Length*—The path length is defined for its use in the calculation of the ~~Average Traversal Speed.~~average traversal speed. It is the measurement of a path down the center of the defined ~~area.~~ area, not the actual path traversed by the A-UGV. Curved traversal distances are not measured.

4.3.6.1 For the ~~Straight Aisle, Path Length~~straight aisle, path length is $\sout{z}ly_{\sout{y}a}$ (see Fig. ~~1~~2).



NOTE 1—The thick black lines indicate the physical barriers or lines along which virtual barriers or floor markings are set.

FIG. ~~7~~8 Diagram of Test Method for Navigation through a Dual Intersection with Interior Chamfers Defined by d_1 and d_2

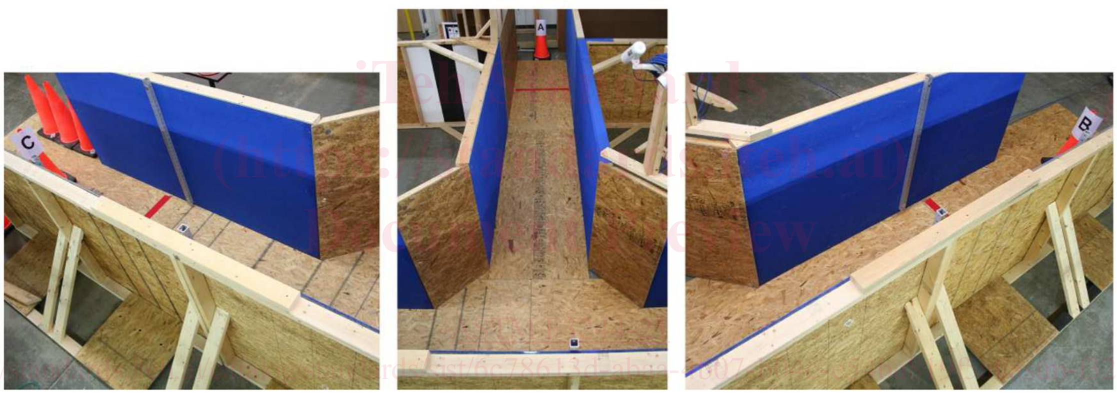


FIG. 9 Example: Dual Intersection with Interior Chamfers Apparatus with Physical Barriers

4.3.6.2 For the ~~Intersecting Aisles~~intersecting aisles where θ is 90°, ~~Path Length~~path length is (~~2~~ly_{a} – y_a/2) + (~~2~~lx_{a} – x_a/2) (see Figs. ~~2~~-3-~~7~~8). For intersecting aisles where θ is not 90°, a similar calculation using the defined area's center line should be made.

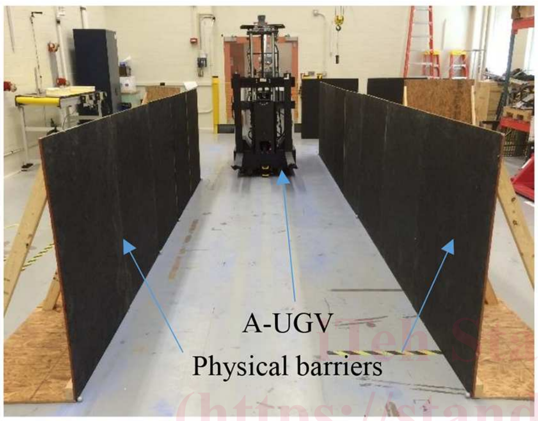
4.3.6.3 For larger, more complex areas, the path length is measured by recording the approximate route taken by the A-UGV through the apparatus, calculated using the center line of the defined area encompassed.

4.3.7 *Traversal Speed*—The speed, measured in meters per second, determined by dividing the ~~Path Length~~path length by the completion time for a single repetition. Average ~~Traversal Speed~~traversal speed is calculated by dividing the ~~Path Length~~path length by the ~~Average Time,~~average time, where average time is the ~~Total Duration~~total duration for n repetitions, divided by n.

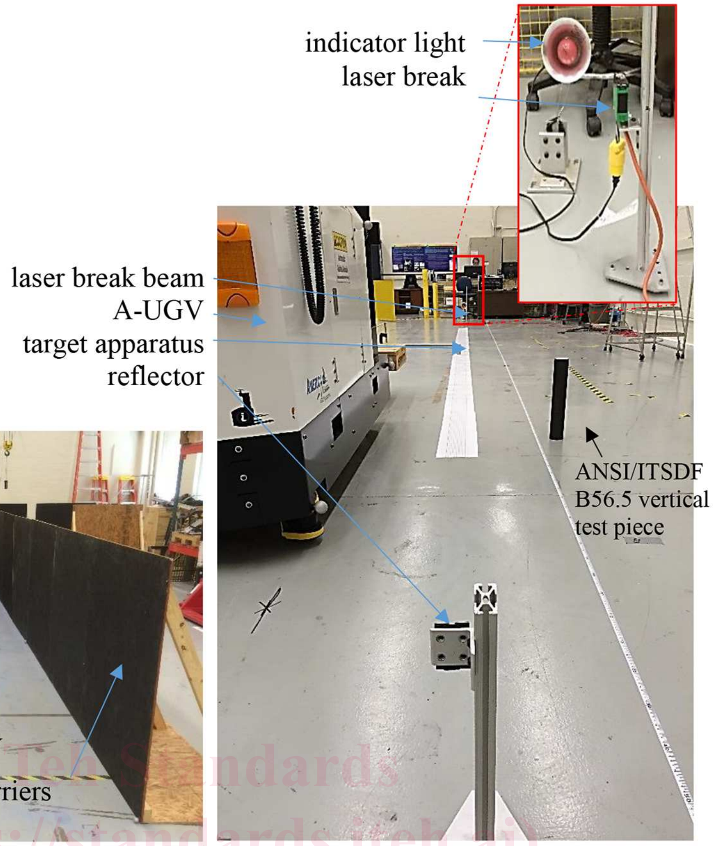
4.3.8 *Intended Behavior*—The test requestor can set success criteria for each test, such as passing the goal line to reach the goal location without colliding with the boundaries or stopping in place when an impairment is encountered that does not allow the A-UGV to reach the goal. There are two dimensions of intended behavior to be defined:

4.3.8.1 *Goal Reaching Efficacy*—Success criteria to define whether or not the A-UGV must reach the goal location to signify a complete repetition. The test requestor may require the A-UGV to not reach the goal after an impairment is encountered, such as a communication drop out.

4.3.8.2 *Maximum Task Time*—The maximum allowed completion time for a successful repetition. This is an optional success criteria that can be set by the test requestor as part of the intended behavior of the A-UGV, but is not required.


A-UGV
Physical barriers

(*a*)


indicator light
laser break
laser break beam
A-UGV
target apparatus
reflector
ANSI/ITSDF
B56.5 vertical
test piece

(*b*)


floor marking
laser line attached
to A-UGV

(c)

FIG. 10 Example of A-UGV Navigation within (a) Physical Barriers, (b) Virtual Barriers, (c) Floor Markings

TABLE 1 Number of Repetitions Required to Achieve Different Confidence Measured Against the Probability of Success Threshold with Zero Failures

		Probability of Success Threshold		
		0.99	0.95	0.9
Confidence	0.99	459	90	44
	0.95	299	59	29
	0.9	230	45	22
	0.85	189	37	19
	0.8	161	32	16

4.3.8.3 *Additional Success Criteria*—The test requestor may set additional success criteria that requires particular observable responses from the A-UGV, such as:

(1) The A-UGV performed the navigation task while maintaining a specified task pace; for example, without interruption, not at a slower pace, or not delayed.

(2) The A-UGV performed the navigation task with an acceptable amount of task delay; for example, the A-UGV stops in route to the goal for too long (for example, 2 s) when no obstacle is the cause for stop.

(3) The A-UGV performed the navigation task without human intervention; for example, the A-UGV continues task performance on its own.

(4) The A-UGV performed the navigation task with human intervention; for example, the A-UGV was helped to remove a stop by a test technician or other person as expected.

4.3.9 *A-UGV Aisle Heading/Direction*—In straight aisles, the A-UGV may be commanded to use a particular heading moving forward or in reverse. The heading and direction that is used by the A-UGV will be recorded for each test.

4.3.10 *A-UGV Turn Direction*—In turning between intersecting aisles (see Figs. ~~2-~~3-~~7~~8), the A-UGV can be commanded to traverse between the start line (A) and either of the two possible goal lines (B or C), each of which result in a different route. The test requestor can test both routes with both vehicle orientations to determine the symmetry of A-UGV operation, which would encompass two separate tests.

4.3.11 *Test Flexibility*—Under some circumstances, a test requestor may request a test be carried out using the intersection shape described in 4.3.2 but with different intersection angle at a value other than 90°. Such a test is allowed when requested by the test requestor prior to beginning a test, although with the provision that the area definition and test completion follow the methods set out in 4.3.

4.3.12 *Increasing Complexity of Navigation Areas*—Areas larger than the single and dual intersection aisles shown in Figs. 2-8 can also be used as defined areas for navigation evaluation. Dimensions shall be recorded for every segment of the defined area in a diagram provided on the test report. An example of a larger defined area is shown in Fig. 11. The length of all aisles must adhere to the minimum course dimensions described in 6.5 (that is, aisle lengths must be at least four times the A-UGV length and not less than 4 m). Multiple start and goal lines can be specified if multiple routes are available to exit the start location or enter the goal location, as shown in Fig. 11.

4.3.13 ~~*Multiple Areas*—~~*A-UGV Positioning Data*—The ~~tests described in this test method anticipate only a single area route will be chosen for the test. Future standard test methods may be developed that combine multiple areas or apparatuses to define more complex areas and routes.~~position of the A-UGV throughout the defined area test apparatus should be recorded throughout the test using methods such as video recording, motion capture, or self-reported location information from the A-UGV, or combinations thereof. The type of recording method should be noted on the report form.

5. Significance and Use

5.1 A-UGVs operate in a wide range of applications such as manufacturing facilities and warehouses. Fig. ~~8~~1 shows three example A-UGV types and test apparatus sizes to test A-UGVs intended for different vehicle tasks, types, sizes, and capabilities. Such sites can have both defined and undefined areas that are structured and unstructured. The testing results of the candidate A-UGV shall describe, in a statistically significant way, the ability of the A-UGV to ~~traverse the commanded path.~~ navigate through a defined area with or without impairments. Whether or not an A-UGV is able to deviate from its path, or uses features of the local

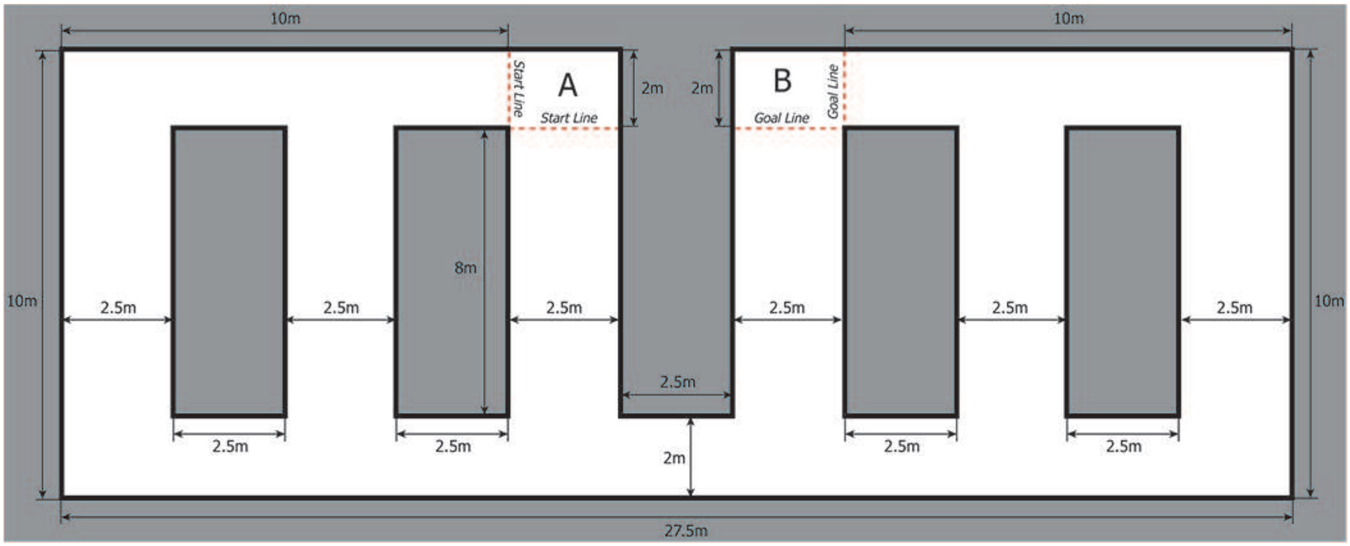


FIG. 11 Example Diagram of Test Method for Navigation through a Larger, More Complex Defined Area

environment as input to its navigation method or both, should not result in a different test method. Rather, the capabilities of the A-UGV to adapt its navigation method in a given environment will be objectively determined by its performance in the test method.

5.2 Three different manners in which a test method apparatus can be rendered are specified for use: physical boundaries, virtual boundaries, and floor markings (see Section 6 for apparatus specifics). Two types of impairments are specified that can be utilized as the defined area as part of a navigation test: obstacles and communication impairments (see Section 7~~The test method(s)~~ for more detail). The apparatuses and impairments chosen shall be appropriate to the application and environment in which the A-UGV will be used.

5.3 These test methods address A-UGV performance requirements expressed by A-UGV manufacturers and potential A-UGV users. The performance data captured by these test methods are indicative of the capabilities of the A-UGV and the application represented by the test.

5.4 The test apparatuses are scalable to constrain A-UGV sizes in defined areas to meet current and advanced next generation manufacturing and distribution facility operations.

5.5 The standard apparatuses are specified to be easily fabricated to facilitate self-evaluation by A-UGV developers and users and provide practice tasks for A-UGV developers, users, and potential users that exercise A-UGV actuators, sensors, and controls.

5.6 Although the test methods were developed first for A-UGVs, they may also be applicable to mobile manipulators and other types of industrial automated mobility equipment, as well as in other domains.

6. Apparatus

NOTE 1—Boundaries for the test methods can be created physically, by virtual lines, or with floor markers.

6.1 *Physical Boundaries*—All test methods can be implemented as physical boundaries. Fig. 9 shows an example. The environment can be constructed from flat, bendable materials such as thin wood panels, which, when coated uniformly, can be reliably detected by the A-UGV being tested and bound the ~~Defined Area~~defined area such that any part of the vehicle crossing the boundary will be detected. The height of the physical boundaries (*b1,b2,* etc.) from the ground to the top of the wall/panel is recorded (h_{b1}, h_{b2}, etc.) and marked in the diagram (see Fig. 12). Multiple heights of each segment of boundaries can be specified as needed.

6.2 *Virtual Boundaries (Laser Beams)*—Boundaries of the environment may be defined by several laser beam sensors, each having a laser transceiver at one end and a reflector on the opposite end as exemplified in Fig. 10(b). The lasers are set up to bound the