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14. ABSTRACT
This Test Operating Procedure (TOP) describes a systematic approach to assess the safety and performance of autonomous Unmanned Ground Vehicles (UGVs) in a controlled test environment, to determine their capability of operation on public transportation infrastructure (PTI). The objective is to ensure that the design of each UGV includes positive measures to enhance system safety, and that hazards which may exist are identified and characterized, so they can be mitigated or eliminated to an acceptable level of risk by the appropriate stakeholders.

15. SUBJECT TERMS
unmanned ground vehicle, UGV, public transportation infrastructure, PTI, autonomous, semi-autonomous, driver-assist, highway, rural highway, arterial, city streets, urban, controller area network, CAN, robotic operating system, ROS, global positioning system, GPS, central tire inflation system, CTIS

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U.S. ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

*Test Operations Procedure 02-2-547 5 March 2020
DTIC AD No.

CREATION OF AUTONOMOUS VEHICLE TESTING SCENARIOS

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1. SCOPE.

This Test Operations Procedure (TOP) describes a systematic approach to assess the safety and performance of autonomous Unmanned Ground Vehicles (UGVs) in a controlled test environment, to determine their capability of operation on Public Transportation Infrastructure (PTI). The objective is to ensure that the design of each UGV includes positive measures to enhance system safety, and that hazards which may exist are identified and characterized, so they can be mitigated or eliminated to an acceptable level of risk by the appropriate stakeholders.

1.1 Purpose.

The purpose of this document is to provide a systematic approach to testing UGVs in order to ensure that the overall safety of the system is adequate and that the performance of the UGV meets expectations. These activities are designed to address the autonomous and semi-autonomous features of the vehicles under test, and should only be performed after the base vehicle's automotive performance has been characterized. Autonomous features would be vehicle behaviors that are meant to be performed without human oversight. This document describes test scenarios designed to determine the vehicle's behavior as if the vehicle was operating on PTI. This document also provides uniform procedures for developing and implementing a test methodology of sufficient comprehensiveness to identify hazards of autonomous subsystems and to verify performance of the system meets system requirements.

1.2 Applicability.

This document is appropriate for application to UGVs capable of autonomous/semi-autonomous operation that may be used on PTI. PTI includes three categories: interstate freeways/limited access highways/rural highways, arterial/urban/city streets, and parking lots. This document does not contain any guidance on licensure or recommendations for operating in real world PTI. More information on UGV testing can be found in TOP 02-2-540[1**].

1.3 Activities Addressed.

The information contained herein applies to testing of autonomous, semi-autonomous, and driver-assist systems for use on PTI. As with any test program, tailoring of test procedures to the specific needs of the system and its intended use are encouraged.

** Superscript numbers correspond to Appendix E, References.

1.4 Limitations.

a. This document is only for the testing of UGVs. Methodologies for the testing of Unmanned Aerial Vehicles (UAVs) or Unmanned Submersible Vehicles (USVs) are not covered in this document. This document does not apply to automated subsystems that do not directly affect people or objects outside of the vehicle, such as automated internal weapon loading systems or automated tracking subsystems, or automated driver-assist functions that require full-time on-board driver attention to perform a task such as cruise control, anti-lock brake systems, or self-leveling systems.

b. This document is applicable to testing of multiple UGVs working in the vicinity of each other. However, testing of multiple UGVs working in cooperation is not addressed in this document.

c. This document does not include baseline automotive performance. Vehicle performance must be known before these test scenarios are executed, to include but not limited to: speed, acceleration, braking, and steering performance. This is to ensure that issues observed during testing are attributable to the autonomous system, and not a limitation of the base platform.

2. FACILITIES AND INSTRUMENTATION.

2.1 Test Facilities and Conditions.

a. Existing test facility types should be used when possible. Instrumentation and system operational equipment procedures for each facility should be created and may vary based on the type of equipment being tested.

b. Courses that are being used for UGV testing must be accurately digitally modeled in order to be used to verify the UGV cognitive abilities when applicable. This digital model will be used as the control that can be compared to the UGV's perception in order to determine if there are variances between the UGV's perception and reality. These facilities may be instrumented and calibrated to include Radio Frequency (RF) and meteorological monitoring stations in order to accurately depict changing conditions of the course.

c. Video should be recorded for the entire test event in order to record mishaps and incidents, while also providing situational awareness to personnel monitoring the test from a safe location in real time, if possible. External video coverage (and internal where applicable) of the SUT scenario should begin just prior to the beginning of the scenario and end when the scenario has concluded.

2.2 Instrumentation.

a. Instrumentation requirements for PTI testing of UGVs will rely extensively on the system's sensors to provide information regarding the environment in which the UGV is operating. All pertinent vehicle bus data to include but not limited to Controller Area Network (CAN), Robotic Operating System (ROS), etc. should be collected as required. Additional instrumentation should be employed to measure the following as applicable, but not limited to:

(1) All vehicles' position (geometric center) on test course (acceptable error is 1/5 of system width).

(2) Communications latency between operator control unit and vehicles (± 5 microseconds).

(3) Communications signal strength (decibels (voltage level) referenced to 1 microvolt per meter (dBμV/m).

(4) All vehicles' speed (± 0.2 kilometers per hour (km/hr)).

(5) All vehicles' acceleration (± 5 percent of reading or 0.1 *g* (whichever is greater)).

b. A Global Positioning System (GPS) device will be used to mark the position of the vehicles used in testing (1 meter (m) resolution).

c. In general, instrumentation will continue to be used in traditional physical test roles to gather pertinent component level data using accelerometers, thermocouples, etc.

d. Prior to testing, a digital spectrum analyzer will be used to examine the spectral composition of RF in the testing area. The data collected will be analyzed to ensure that RF signals in the testing area will not cause interference with the test item.

3. REQUIRED TEST CONDITIONS.

The test item configuration will be as follows:

a. The system shall be in a complete and representative configuration.

b. The software and hardware versions for all subsystems shall be recorded and remain unchanged during testing. If software or hardware revisions are made, the test officer may decide that test scenarios need to be repeated for the new configuration.

c. The vehicle should be set up properly for the scenario, including but not limited to: Central Tire Inflation System (CTIS) or tire pressures, track tension, payload, sensor alignment, sensor or actuator calibrations, and operational mode.

d. A system inspection will be conducted to verify basic automotive vehicle functions (acceleration, braking, steering, etc.).

e. Safety protocols such as emergency stops and driver takeover will be verified to be operational.

f. Additional safety features such as safety drivers and test course exclusive use will be assessed as needed through a formal risk assessment.

4. TEST PROCEDURES.

a. The UGV under test will be required to appropriately and safely respond to various environmental stimuli typically encountered in normal vehicle road use based on the capability development document. Standard straight, curved, backward, and turning maneuvers will be tested with various combinations of sub-maneuvers, speeds, weather, road conditions, light levels, and obstacles present. Table 1 presents a list of test maneuvers, and Table 2 contains a list of parameters. These tables can be used as general guidelines and scenarios can be added and/or removed as necessary (such as wind gusts, blowing dirt/dust, tire under inflation, etc.). A Design of Experiment (DOE) built from Tables 1 and 2 should be considered when the test item has been determined, and its capabilities have been identified. Parameter definitions can be found in Appendix B. The first test scenario will include a straight maneuver with clear weather, dry road, daylight, and no obstacle at the speed most appropriate to the intended mission. Vehicle performance limitations identified during maneuvers will be used to tailor future test scenarios. Further test scenarios for the specified maneuver / sub-maneuver combination will vary speed, weather, road conditions, light levels, and obstacles as required for the mission environment. Example scenarios are depicted in Appendix C. The decision to move onto the next scenario will be made at the discretion of the test officer/field engineer.

TABLE 1. TEST MANEUVERS

MANEUVER	SUB MANEUVER
Straight Curve Left Turn Right Turn Reverse	None
	Lane Change
	Merge
	Braking
	Acceleration
	Deceleration

TABLE 2. TEST PARAMETERS

SPEED (miles per hour (mph))	WEATHER	ROAD CONDITION	LIGHT	OBSTACLE	ROAD SURFACE
X ≤ 10	Clear	Dry	Daylight	None	Paved
10 < X≤ 25	Fog	Wet	Night	Animal (S/D)	Improved Gravel
25 < X ≤ 35	Rain	Snow	Twilight	Child (S/D)	
35 < X ≤ 55	Snow	Ice	Dawn	Adult (S/D)	
55 < X		Flat	Dusk	Cyclist (S/D)	
		Hilly		Vehicle (S/D)	
		Dust		Object (S/D)	
				Signage[a]	
				Forced Failure[a]	

NOTES:
(S/D) denotes inclusion of both static (S) and dynamic (D) versions of specified obstacle.
[a] These obstacles are accompanied by additional instructions located in paragraphs 4.5 and 4.6.

b. Based on the test goals and required data, test officers, subject matter experts, and/or evaluators should decide which test maneuvers, sub maneuvers, and test parameters are needed. Design of Experiments should then be used to determine the test sample size and combination of conditions for each test/subtest. The number of runs required in the DOE is based on test parameters selected, requested statistical power, and additional statistical assumptions. Example DOEs are depicted in Appendix D. Modeling and simulation may also be used where appropriate.

4.1 Straight Movement.

Used to demonstrate the test item is capable of unassisted forward locomotion along a straight path.

a. Determine the straight maneuver scenarios that will be tested from Table 1 as defined by mission needs.

b. Set up a test track in accordance with the following specifications:

(1) One or more lanes.

(2) Straight path.

(3) Enough space for the test item to reach target speed before encountering path.

(4) Scenario specific parameters.

c. Run the test item along the test track.

d. Repeat with different straight maneuver scenarios as necessary.

4.2 Curved Movement.

Used to demonstrate the test item is capable of unassisted forward locomotion along a curved path.

a. Determine the curved maneuver scenarios that will be tested from Table 1 as defined by mission needs.

b. Set up a test track in accordance with the following specifications:

(1) One or more lanes.

(2) Curved path turning both left and right.

(3) Various turning radii.

(4) Various curve lengths.

(5) Enough space for the test item to reach target speed before encountering path.

(6) Scenario specific parameters.

c. Run the test item along the test track.

d. Repeat with different curved maneuver scenarios as necessary.

4.3 Turning Movement.

Used to demonstrate the test item is capable of properly turning at an intersection.

a. Determine the left turn and right turn maneuver scenarios that will be tested from Table 1 as defined by mission needs.

b. Set up a test track in accordance with the following specifications:

(1) One or more lanes.

(2) An intersection of two or more roads.

(3) Enough space for the test item to reach target speed before encountering intersection.

(4) Scenario specific parameters.

c. Run the test item along the test track, perform a right hand turn at the intersection, and assess its performance.

d. Run the test item along the test track, perform a left hand turn at the intersection, and assess its performance.

e. Repeat with different left maneuver and right maneuver scenarios as necessary.

4.4 Reverse Movement.

Used to demonstrate the test item is capable of unassisted backward locomotion along a straight path and curved path.

a. Determine the backward maneuver scenarios that will be tested from Table 1 as defined by mission needs.

b. Set up a test track in accordance with the following specifications:

(1) One or more lanes.

(2) Straight paths.

(3) Curved paths turning left and right.

(4) Various turning radii.

(5) Various curve lengths.

(6) Enough space for the test item to reach target speed before encountering path.

(7) Scenario specific parameters.

c. Run the test item backwards along the test track and assess its performance.

d. Repeat with different reverse maneuver scenarios as necessary.

4.5 Signage.

Vehicles on public roads must obey the set traffic signals and laws. The purpose of these tests is to demonstrate the test item can interpret different light signals and road signs.

a. Set up a test track in accordance with the scenario requiring signage. Additionally insert:

(1) Enough space for the test item to reach target speed before encountering a sign or light.

(2) Stop signs and traffic lights appropriate to mission environment, separated at a minimum of 60 m for scenarios involving speed under 90 km/hr, 90 m for scenarios involving speed of 90+ km/hr.

b. Run the test item along the test track and assess its performance.

c. Repeat with other traffic signs as defined by mission requirements and operational locations as necessary.

4.6 Forced Failure.

Failures varying in severity cause many unforeseen impacts on transportation infrastructure. Since testing all permutations of failure is unobtainable in a realistic amount of time, modeling and simulation techniques should be used to minimize the number of live scenarios. The purpose of these tests is to determine how the test item would react to various spontaneous failures. Examples of such failures would be sensors or cameras losing power or providing unexpected data, a flat tire, suspension failure, or loss of a cooling fan. These instructions are necessary only when forced failure is used in a scenario.

a. Create an accurate virtual or live test track in accordance with the following specifications:

(1) One or more lanes.

(2) Straight path.

(3) Curved paths turning left and right.

(4) An intersection of three or more lanes.

b. Run the test item along the test track.

c. Simulate a failure in the test item appropriate to mission needs and assess its performance.

d. Re-run simulation with additional failures as necessary.

5. DATA REQUIRED.

a. Documentation will be provided detailing all aspects of testing, including but not limited to the following:

(1) UGV serial number.

(2) Photographs of test site and setup.

(3) Description of RF environment.

(4) Video and data link operating frequency.

(5) Any failure or limitation of the vehicle or its subsystems during testing.

(6) Metrological conditions (temperature, humidity, visibility, light) and roadway conditions (paved, gravel, wet, dry flat, sloped, etc.).

(7) Speed and position of test vehicles and obstacles.

(8) Pertinent vehicle communication bus (CAN, ROS, etc) data.

b. Additional aspects of testing that could be included only when obstacles, signage, or forced failure are involved are as follows:

(1) Observation of obstacle/signage, verified from vehicle communication bus.

(2) Recognition of obstacle/signage, verified from vehicle communication bus.

(3) Correct response to obstacle/signage, verified from vehicle communication bus.

(4) Time to detect forced failure, verified from vehicle communication bus.

(5) Recognition of correct forced failure, verified from vehicle communication bus.

(6) Correct response to failure, verified from vehicle communication bus.

(7) Time to respond correctly according to mission capabilities, verified from vehicle communication bus.

6. PRESENTATION OF DATA.

a. Describe the inspection, specific test procedures, and results for each item using narration, tables, photographs, charts, and graphs as appropriate or as outlined in procedures and data required.

b. Reduce, summarize, and analyze data from each subtest appropriate to the subtest data topic and failure definitions derived specifically for the item and the subtest category. Unique analytical tools (e.g., models, simulations, statistical techniques) should be described in sufficient detail to enable the reader to understand the basis for the analysis.

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APPENDIX A. ABBREVIATIONS.

CAN	Controller Area Network
CTIS	Central Tire Inflation System
D	dynamic
DOE	Design of Experiment
Euro NCAP	European New Car Assessment Programme
FDOT	Florida Department of Transportation
ft	feet
GPS	Global Positioning System
in./hr	inches per hour
km/hr	kilometers per hour
m	meter
mph	miles per hour
NHTSA	National Highway Traffic Safety Administration
NOAO	National Optical Astronomy Observatory
OFCM	Office of the Federal Coordinator for Meteorological Services and Supporting Research
PTI	Public Transportation Infrastructure
RF	Radio Frequency
ROS	Robotic Operating System
S	static
SAE	Society of Automotive Engineers International
TOP	Test Operations Procedure
TxDOT	Texas Department of Transportation
UAV	Unmanned Aerial Vehicle
UGV	Unmanned Ground Vehicle
USV	Unmanned Submersible Vehicle

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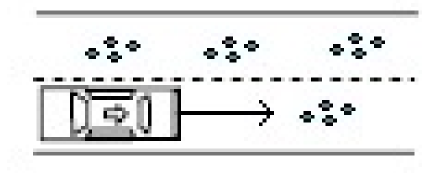
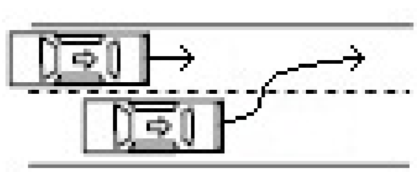
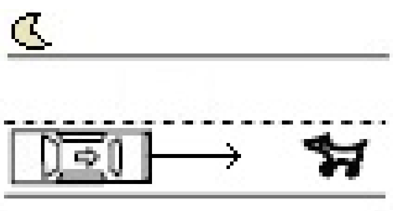
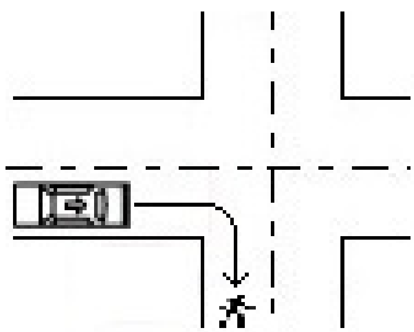
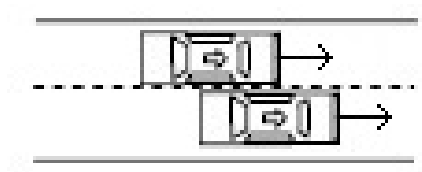
APPENDIX B. TEST PARAMETER DEFINITIONS.

TERM	DEFINITION
Clear	No precipitation and no visibility obstructions.
Fog	Visible aggregate of minute water particles with reduced visibility under 0.625 miles.
Rain	Liquid precipitation of at least 0.10 inches per hour (in./hr).
Light Rain	Liquid precipitation of 0.10 in./hr. From scattered drops that do not completely wet an exposed surface to a condition where individual drops are easily seen.
Moderate Rain	Liquid precipitation between 0.11 in./hr to 0.30 in./hr. Individual drops are not clearly identifiable. Spray is observable just above pavements and other hard surfaces.
Heavy Rain	Liquid precipitation of more than 0.30 in./hr. Precipitation seems to fall in sheets. Individual drops are not identifiable. Spray of several inches is observed over hard surfaces.
Snow (Weather)	Solid precipitation with reduced visibility.
Light Snow	Solid precipitation and reduced visibility to greater than 0.5 miles.
Moderate Snow	Solid precipitation and reduced visibility to between 0.5 miles and 0.25 miles.
Heavy Snow	Solid precipitation and reduced visibility to under 0.25 miles.
Dry	Road is visibly dry.
Wet	Road has standing/constant flowing water present.
Snow (Road)	Road has un-melted snow present.
Ice	Road has un-melted ice present with absence of snow.
Dust	Road has loose dust on the surface, that will be sent airborne by a lead vehicle.
Daylight	Ambient light level of 10000 lux.

APPENDIX B. TEST PARAMETER DEFINITIONS.

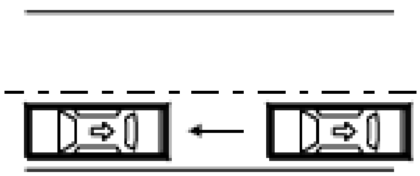
TERM	DEFINITION
Twilight	Ambient light level of 10 lux.
Night	Ambient light level less than 1 lux.
Animal	Any simulated fauna appropriate to mission environment.
Child	A mannequin dressed in a black shirt and blue trousers, 3 feet, 10 inches in height. Clothing may be tailored to match environment.
Adult	A mannequin dressed in a black shirt and blue trousers, 6 feet in height. Clothing may be tailored to match environment.
Cyclist	A mannequin mounted on any transport with less than four wheels.
Vehicle	Any transport with four or more wheels traveling parallel to the test item or perpendicular to the test item's path.
Object	Any solid item non-native to the road appropriate to mission environment.
Signage	Typically encountered lights/signs as appropriate to mission environment.
Forced Failure	Mission critical elements no longer function.

APPENDIX C. EXAMPLE SCENARIOS.

	**<u>Scenario: Straight, No Sub Maneuver, Clear, Wet, Daylight, No Obstacle</u>** UGV is traveling at scenario speed straight on a wet road. Daylight, clear weather. UGV continues straight.
	**<u>Scenario: Straight, Attempted Lane Change, Clear, Dry, Daylight, Dynamic Vehicle</u>** UGV is traveling at scenario speed straight on a dry road. Daylight, clear weather. UGV attempts lane change and encounters a vehicle traveling in the same direction.
	**<u>Scenario: Straight, No Sub Maneuver, Clear, Dry, Night, Static Animal</u>** UGV is traveling at scenario speed straight on a dry road. Night, clear weather. UGV encounters an animal.
	**<u>Scenario: Right Turn, No Sub Maneuver, Clear, Dry, Daylight, Static Adult</u>** UGV is traveling at scenario speed straight on a dry road approaching an intersection with a crosswalk. Daylight, clear weather. UGV attempts right turn and encounters a pedestrian in the crosswalk.
	**<u>Scenario: Straight. No Sub Maneuver, Clear, Dry, Daylight, Dynamic Vehicle</u>** UGV is traveling at scenario speed straight on a dry road. Daylight, clear weather. Vehicle traveling in same direction drifts towards UGV.

Note: Arrow indicator on vehicle points to the front of the vehicle.

APPENDIX C. EXAMPLE SCENARIOS.

	**Scenario: Reverse. No Sub Maneuver, Clear, Dry, Daylight, Static Vehicle** UGV is traveling in reverse at scenario speed straight on a dry road. Daylight, clear weather. UGV encounters a vehicle.

Note: Arrow indicator on vehicle points to the front of the vehicle.

APPENDIX D. EXAMPLE DESIGN OF EXPERIMENTS.

Example Number 1

Test Goal: Determine if UGV can observe dynamic obstacles during operations

- **Response Variable:** Observation of dynamic obstacle, verified from vehicle communication bus (Y/N) during straight maneuver (no sub maneuver)
- **Test Parameters:** Visibility (Clear, Obscurants), Obstacle, (Adult, Car, Cyclist), Vehicle Speed (20, 30, 40)

TABLE D-1. EXAMPLE TEST DESIGN 1

Visibility	Obstacle	Vehicle Speed (mph)		
		20	30	40
Clear	Adult	6	6	6
	Car	6	6	6
	Cyclist	6	6	6
Obscurants	Adult	6	6	6
	Car	6	6	6
	Cyclist	6	6	6

Sample Size: 108

Statistical Assumptions: 85% probability of success and 20% difference to detect with 80% confidence to achieve 80% power

APPENDIX D. EXAMPLE DESIGN OF EXPERIMENTS.

Example Number 2

Test Goal: Determine time it takes UGV to respond to static obstacles

- **Response Variable:** Time to respond correctly according to mission capabilities, verified from vehicle communication bus during straight maneuver (no sub maneuver)
- **Test Parameters:** Light conditions (Day, Night), Maneuver, (Straight, Reverse, Curve), Obstacle (Adult, Vehicle, Animal)

TABLE D-2. EXAMPLE TEST DESIGN 2

Run	Light Conditions	Maneuver	Obstacle
1	Day	Straight	Adult
2		Straight	Vehicle
3		Reverse	Vehicle
4	Night	Curve	Animal
5		Straight	Animal
6		Curve	Adult
…	…	…	…
94	Night	Straight	Adult
95		Reverse	Vehicle
96		Reverse	Animal

Sample Size: 96

Statistical Assumptions: 95% probability of success and 10% difference to detect with 80% confidence to achieve 80% power

APPENDIX E. REFERENCES.

1. TOP 02-2-540, Testing of Unmanned Ground Vehicle (UGV) Systems, 12 February 2009.

For information only (related publications).

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h. Texas Department of Transportation (TxDOT), May 2017. “Manual Notice 2017-1”. http://onlinemanuals.txdot.gov/txdotmanuals/smk/manual_notice.htm.

i. Waymo, Oct. 2017. “Safety Report - Waymo”. waymo.com/safetyreport/.

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APPENDIX F. APPROVAL AUTHORITY.

CSTE-CI 5 March 2020

MEMORANDUM FOR

Commander, U.S. Army Operational Test Command
Director, U.S. Army Evaluation Center
Commanders, ATEC Test Centers
Technical Directors, ATEC Test Centers

SUBJECT: Test Operations Procedure 02-2-547, Creation of Autonomous Vehicle Testing Scenarios, Approved for Publication

1. Test Operations Procedure (TOP) 02-2-547, Creation of Autonomous Vehicle Testing Scenarios, has been reviewed by the U.S. Army Test and Evaluation Command (ATEC) Test Centers, the U.S. Army Operational Test Command, and the U.S. Army Evaluation Center. All comments received during the formal coordination period have been adjudicated by the preparing agency.

2. Scope of the document. This TOP describes a systematic approach to assess the safety and performance of autonomous Unmanned Ground Vehicles (UGV) in a controlled test environment, to determine their capability of operation on Public Transportation Infrastructure. The objective is to ensure that the design of each UGV includes positive measures to enhance system safety, and that hazards which may exist are identified and characterized, so they can be mitigated or eliminated to an acceptable level of risk by the appropriate stakeholders.

3. This document is approved for publication and has been posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at https://vdls.atc.army.mil/.

4. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-CI), 6617 Aberdeen Boulevard-Third Floor, Aberdeen Proving Ground, MD 21005-5001; or e-mailed to usarmy.apg.atec.mbx.atec-standards@mail.mil.

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Integration (DCI)

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