REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

The public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Department of Defense, Washington Headquarters Services, Directorate for information on Operations and Reports (0704-0188), 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to any penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.
PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ADDRESS.

1. REPORT DATE *(DD-MM-YYYY)*
03-02-2022

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE
Test Operations Procedure (TOP)
02-2-548 Leader-Follower Unmanned Ground Vehicle (UGV) Gap Distance and Lateral Deviation Measurements

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHORS

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Automotive Directorate (TEDT-AT-ADU)
U.S. Army Aberdeen Test Center
6943 Colleran Road
Aberdeen Proving Ground, MD 21005-5059

8. PERFORMING ORGANIZATION REPORT NUMBER
TOP 02-2-548

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Policy and Standardization Division (CSTE-TM)
U.S. Army Test and Evaluation Command
2202 Aberdeen Boulevard
Aberdeen Proving Ground, MD 21005-5001

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
Same as item 8

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution Statement A. Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT
This TOP describes procedures for measuring gap distance and cross-track error of Unmanned Ground Vehicles (UGVs) with respect to an intended path of travel generated by a lead vehicle.

15. SUBJECT TERMS

Unmanned Ground Vehicles, Leader, Follower, Gap Distance, Cross-track Error

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	B. ABSTRACT	C. THIS PAGE			19b. TELEPHONE NUMBER *(include area code)*
Unclassified	Unclassified	Unclassified	SAR	29	

(This page is intentionally blank.)

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

*Test Operations Procedure 02-2-548 3 February 2022
DTIC AD No.

LEADER-FOLLOWER UNMANNED GROUND VEHICLE (UGV) GAP DISTANCE AND LATERAL DEVIATION MEASUREMENTS

* Approved for public release; distribution unlimited.

1. SCOPE.

Procedures are provided for measuring the longitudinal and lateral path-following performance of Unmanned Ground Vehicle (UGV) follower vehicle(s) traversing a path defined by a lead vehicle.

1.1 Purpose.

a. This Test Operations Procedure (TOP) describes scenarios used to assess a UGV system's ability to navigate a route during unmanned operation, and is specific to multiple-vehicle convoys where a leader (typically the first vehicle in a convoy operated manually with no pre-set path) generates a route for follower vehicles. The manually driven path of the leader vehicle is recorded via on-board test instrumentation. As subsequent follower vehicles attempt to navigate the path, their positions are also recorded. The data are post-processed to characterize path following performance and safety.

b. Driverless vehicles offer the potential to reduce the number of personnel required to complete a mission, such as removing humans from hostile and hazardous environments. However, current autonomous driving systems, particularly those undergoing developmental testing, have situational awareness inferior to that of a human driver. Situational awareness consists of three major components: perception of the environment, comprehension of the situation, and projection of future events. Autonomous systems excel at perception by use of sensors that perceive the environment in ways that humans cannot, including ranging sensors such as radar and Light Detection and Ranging (LIDAR), non-visible light spectrum sensors such as infrared, and information about the environment received through vehicle-to-vehicle (V2V) and vehicle-to-environment communication. Autonomous systems, however, currently lack the ability to comprehend the environment and anticipate future events with the effectiveness of a human driver. Of particular difficulty for autonomous systems are edge cases, or situations rarely encountered, that may not have been considered during the systems' development. Artificial intelligence and self-learning capability may change this in the future, but will require significant development from current levels. Consequently, these systems and situations can be extremely dangerous. Thorough field-testing, characterization, and analysis is critical to safely fielding autonomous driving systems.

c. Characterization of UGV positional behavior in a dynamic convoy setting is critical when assessing system safety. Significant deviation from a designated path and insufficient clearance between vehicles may be hazardous. Test results are specific to each platform (vehicle) and system version (hardware/software/firmware). Data are used to establish safe maximum operating speeds and minimum follower gaps (distance or time based).

1.2 Limitations.

a. This TOP generally applies to wheeled ground vehicle systems (not aerial or watercraft) tested in fair weather and daylight conditions. If testing is required in conditions other than fair weather and daylight, additional procedures may need to be developed and applied for safety and technical reasons.

b. Tracked and other vehicles capable of pivot steering are not addressed. However, methods in this document may be applied to pivot steering vehicles in certain scenarios.

c. Levels of autonomy are not explicitly limited. Leader-follower systems capable of operating without a driver demonstrate at least Level 3 driving automation (SAE International Surface Vehicle Information Report J3016[1**]). To achieve Level 3 status, the system must be able to actuate controls of the platform (accelerator, brakes, steering, and transmission at minimum), generate a path internally based on current position (navigation solution), be able to receive desired positional information from other vehicle(s) in the convoy, and produce corrective action to achieve desired positions.

d. The TOP applies to systems with a lead vehicle that broadcasts position information to all followers when operating along a route or when the route is completed. The TOP further applies to systems with follower vehicles that generate a path or trajectory based on data sent from the leader, while attempting to maintain a preset gap (either distance or time based) without violating preset boundaries (unique to the System Under Test (SUT)). Boundaries may include a safety corridor defined as a predetermined maximum lateral deviation from the leaders path, as well as minimum and maximum speeds at each position.

e. Procedures in this TOP rely on the ability to receive high-accuracy positioning and timing data from one or more Global Navigation Satellite System (GNSS) constellations. Throughout this TOP, the term Global Positioning System (GPS) refers to GNSS, but any constellation or combination of constellations that provide adequate accuracy may be used. Real Time Kinematic (RTK) corrections in conjunction with GNSS measurements are required to produce the centimeter-level positional accuracy needed for the assessments outlined in this document. It is also necessary that the specific test sites have clear line-of-site to the sky with minimal buildings, foliage canopy, or other obstacles that might impede the radio frequency (RF) propagation between the GPS satellites and UGV platform.

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

a. Facilities for leader-follower UGV testing are not specific to established test courses. Facilities generally include a variety of terrain types such as primary roads, trails, and cross-country, with environmental conditions that include obstacles like dust, mud, and potholes. Each of the terrains and environmental conditions present different challenges for self-driving systems.

b. Ample space at the test sites is required for safe operations if the follower vehicles deviate significantly from the intended path. Ensure all intended areas of operation are a safe distances from obstacles, buildings, infrastructure, and personnel.

** Superscript numbers correspond to Appendix B, References.

c. The RF environment at each test site shall not cause interference with the test items (including Vehicle-to-Vehicle communication or GPS signals).

2.2 Instrumentation.

Devices for Measuring	Recommended Maximum Error of Combined System
Position	± 2 centimeters (cm) (1.9 inches (in.))
Lateral Acceleration	0.05 *g*
Velocity	± 0.16 kilometers per hour (km/h) (0.1 miles per hour (mph))
Yaw, roll and pitch rates	± 0.1 degrees per second

2.2.1 System Positioning and Velocity.

a. Use of RTK GPS with a 5-Hertz (Hz) minimum update frequency is recommended to achieve desired vehicle position and velocity accuracy. When heading data are required, use of a dual antenna GPS receiver with two GPS antennas on the SUT is also recommended. Place the two antennas as far apart as possible on the SUT to minimize calculation error.

b. The RTK GPS base station shall be located in near proximity to the test site, so that the position corrections from the base station are applicable. The base station shall be pre-programmed with exact antenna coordinates or configured to record its own position. Refer to manufacturer specifications and settings to determine the most appropriate configuration. RTK corrections may occur in real-time by broadcasting corrections from the GPS base station to the SUT for onboard processing. Alternatively, position corrections may occur during data post-processing using recorded SUT and base station data. With either method, the positions of all vehicles under test shall be corrected using the same base station.

2.2.2 Controller Area Network (CAN) Bus.

It is recommended that all relevant vehicle CAN bus data are monitored and recorded during testing, pursuant with TOP 01-2-506 Use of Controller Area Network (CAN) Data to Support Performance Testing[2]. These data may include system states (or modes) and preset configurations (e.g., intended gap setting, maximum allowed speed, and any available measurements from embedded sensors). Due to the proprietary nature of these systems, it may be necessary to obtain an interface control document for identifying and interpreting data sources on each CAN bus. Examples of standard automotive CAN buses include J1708, J1939, and OBDII.

2.2.3 SUT Communication.

When possible, record radio communication statistics between test items for assessment of inter-vehicle communication quality, including packets sent, packets received, and packets dropped.

2.2.4 Cameras.

When possible, use video cameras with time stamping to record operator interface display activity, such as warnings, alerts, and system settings. It is recommended that all display locations providing feedback to an operator, safety rider, or persons responsible for monitoring vehicle behavior be recorded. The use of forward-looking cameras to monitor the intended path of travel are also recommended.

2.2.5 Additional Instrumentation.

It is recommended to fit the test vehicles with an independent six degree of freedom (6-DOF) inertial measurement unit (IMU), particularly when lateral acceleration levels are expected to exceed 0.3 *g* or 30 percent of the vehicle's static stability factor (see paragraph 3.3).

2.2.6 Recording System.

Install a data logger capable of recording GPS, CAN bus, IMU, radio communication, and video data on the test vehicles. If RTK corrections are to be applied during post-processing, the GPS base station messages shall also be recorded during the tests.

2.3 Specialized Equipment.

Use a digital spectrum analyzer to assess the RF environment of the test site prior to and during testing, given the dependency of the SUT on wireless V2V communication.

3. REQUIRED TEST CONDITIONS.

3.1 General Vehicle Test Preparation.

a. Review all instructional material issued with the test vehicle by the manufacturer, contractor, or government, as well as reports of previous tests on the same types of vehicles.

b. Conduct vehicle training to ensure all test personnel are familiar and comfortable with technical and operational characteristics of the SUT and with the required test procedures.

c. Prepare and equip the vehicles in accordance with standard use and/or within the specifications presented in the test plan. Fill the fuel tank and other fluid reservoirs.

d. Ensure that the vehicles received the proper break-in operation and that driveline, tires, brakes, and steering and suspension components are in good serviceable condition.

e. Instrument the vehicle with one or two GPS antennas (see paragraph 2.2.1), a GPS receiver, a RF receiver for RTK corrections if correcting in real time, a data logger, CAN Bus connection(s), a network tap for communication information, an IMU (if desired), and video cameras.

f. Verify all necessary wireless communications are adequate and instrumentation/data loggers are functioning properly.

3.2 Test Controls.

a. Test engineers and technicians should familiarize themselves with the following test standards prior to testing:

(1) International Organization for Standardization (ISO) 15622 Intelligent transport systems- Adaptive cruise control systems- Performance requirements and test procedures[3].

(2) ISO 22839 Intelligent transport systems- Forward vehicle collision mitigation systems- Operation, performance, and verification requirements[4].

(3) SAE International J2399 Adaptive Cruise Control (ACC) Operating Characteristics and User Interface[5].

(4) SAE International J3029 Forward Collision Warning and Mitigation Vehicle Test Procedure (Truck and Bus)[6].

(5) SAE International J3063 Active Safety Systems Terms and Definitions[7].

(6) SAE International J3016 Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems.

b. The SUT Operational Design Domain (ODD) should be well established and understood by the test engineers. ODD is defined in SAE International J3016 as, "Operating conditions under which a given driving automation system or feature thereof is specifically designed to function, including, but not limited to, environmental, geographical, and time-of-day restrictions, and/or the requisite presence or absence of certain traffic or roadway characteristics."

c. A well-defined ODD guides test plan development as well as preliminary testing, such as software safety testing, by defining necessary system safety features. For example, if an ODD states that the SUT is intended for use during daylight hours only, determine if the system has adequate preventative measures to remain disabled at night and at dawn/dusk during low-ambient light conditions.

d. Prior to testing, ensure that:

(1) All personnel involved with testing shall receive new user training provided by system developers, when possible. Understanding all capabilities and limitations of each feature is critical to ensure safe testing.

(2) Vehicle identification, payload condition, total vehicle weight, weight distribution, vehicle dimensions (length, width, height) including trailer and/or payload and center-of-gravity characteristics are recorded.

(3) Pertinent automotive settings such as central tire inflation settings and active suspension settings are recorded.

(4) Data collection run logs are prepared to record all pre-test information, conditions of test, test results, observations, and measurements that would be valuable for analysis and assessment.

(5) All test items have the same software versions, matching the intended versions specified in the test plan. It is highly recommended that system software versions not be changed during testing. If software updates are necessary during testing, it is recommended that all tests completed with the previous software be repeated with the latest software versions.

(6) Software version numbers and firmware version numbers for each pertinent system component (e.g., navigation computers, drive-by-wire computers, brake controllers, wireless communication radio transceivers, routers, human interface devices, operational stops, safety checkers) are recorded.

(7) All limitations of the system under test are well vetted and understood. Typically, system developers provide system limitations. Examples include minimum and maximum speeds that system features operate within, maximum achievable acceleration and deceleration, and steer actuator rates. Additional examples include key parameters required for the system to function (e.g., quality communication to a lead vehicle and any other critical vehicles in a convoy, quality GPS reception, and proper robotic mode initialization procedures).

(8) Vehicle operators and test engineers understand all applicable methods to regain manual control and operation of the vehicle (known as driver takeover) and are prepared to disable robotic operation when necessary. Methods include (but are not limited to) applying service brakes, providing steer input, shifting the transmission to neutral, or utilizing system disconnect buttons made available by the manufacturer. Ensure that all methods to regain control are approved by system developers/manufacturers.

(9) Software safety testing is conducted prior to system performance testing, when possible, to ensure that each method of driver takeover operates as expected and in a timely manner. Software testing should also test any conditions expected to disable robotic driving and return the vehicle to a safe state, such as exceeding a maximum lateral deviation from the intended path, also defined as cross-track error value. Any safety features intended to disable the robotic system or initiate an emergency or operational stop shall be verified.

(10) If changes are made to safety-critical software (software which affects the operations of the aforementioned features), software safety testing should be repeated on any affected features.

(11) If a safety corridor, defined as a distance to the left and right of the leader's path within which each robotic follower must remain, is part of the system ODD, force the system outside of the corridor during robotic operation prior to full-system testing. Observe system behavior. If timing requirements exist for the initiation of a safe stop upon exiting the corridor, use methods described later in this TOP for measurement of cross-track error to determine the precise time that a follower exits the corridor. Compare the observed exit time to CAN bus identified emergency stop or state change data to determine any delay.

3.3 Restrictions.

a. Conduct sufficient Maximum Pedal Effort Brake testing of the base vehicle within the intend range of target speeds of the SUT to ensure that the addition of the robotic braking controls do not degrade braking performance or cause non-compliance with other applicable braking standards.

b. If highly-dynamic maneuvers are anticipated during SUT testing, where lateral acceleration exceeds 0.3 *g* or thirty percent of the vehicle Static Stability Factor (SSF), tilt-table, circular steer, and emergency lane change tests (at a minimum) shall be conducted with a human operator prior to SUT testing. Refer to TOP 02-2-002A, Steering and Cornering Behavior[8], for guidance.

c. If vehicle Anti-lock Brake System (ABS) and/or Electronic Stability Control (ESC) systems are necessary risk mitigations to allow testing, assessment on those individual systems shall also be made prior to SUT testing. Refer to TOP 02-2-608, Braking, Wheeled Vehicles[9], TOP 02-2-002A, Steering and Cornering Behavior, and TOP 02-2-718A, Electronic Stability Control[10], for guidance.

d. If tests are to be conducted at night, during inclement weather, or when road surfaces and visibility introduce hazards, risks shall be identified and mitigated with an approved Job Hazard Analysis specific to the SUT. Local safety standard operating procedures (SOPs) (or equivalent) and traffic laws shall be followed. Desirable environmental conditions for test conduct are as follows:

(1) Average wind speed less than 5 meters per second (m/s) (11 mph).

(2) Ambient temperature from 2 to 40 °Celsius (°C) (35 to 104 °Fahrenheit (°F)).

(3) Relative humidity less than 95 percent.

3.4 Safety.

a. SUT operators and test engineers shall receive operational training for the SUT prior to testing. It is recommended that the training be provided by the system manufacturer, and include system functions and capabilities, the ODD, operating procedures, means to enable/disable system features, and means to gain full control of the SUT when necessary (i.e., operator intervention).

b. It is recommended that SUT operators have the means and training to assume manual control of the autonomous test vehicles in less than one second.

c. It is recommended that intervention failure mode analyses be conducted prior to field testing. In addition to the methods listed in paragraph 3.2.c(9) and shutting off the vehicle engine, intervention methods may include an emergency stop (E-stop) button that quickly releases the throttle and engages vehicle brakes or a button that physically disconnects power to control modules or actuators, releasing the throttle and enabling manual braking. If there are no known or adequate intervention methods, the installation of an independent commercial-off-the-shelf wireless relay system may be required to shut down UGV system functions. Verify that safety riders can overpower actuators employed if necessary, so that the throttle can be released and brakes applied.

4. TEST PROCEDURES.

4.1 Background.

The two main objectives addressed by this TOP are measuring the gap distance between each vehicle in the convoy and measuring the lateral path deviation (or cross-track error) of each vehicle compared to the leader's path. The gap distance between each vehicle in the convoy is relevant to avoid inter-convoy collisions, especially during rapid decelerations. Minimizing cross-track error also reduces the likelihood of accidents.

4.2 Definitions.

4.2.1 Vehicle Reference Positions.

Establish vehicle reference positions prior to testing for consistent calculation of gap distance and cross-track error. It is recommended that reference positions be consistent with those assigned by the SUT developer. Examples include the midpoint of the front axle centerline, the midpoint of the rear axle centerline, and the theoretical turn rotation center. Translate GPS measurement point data to the vehicle reference position using Equations 1 through 3, as shown in Figure 1 for the case of the rear axle centerline.

$$R_X = M_X + \left|\overrightarrow{MR}\right| sin(\theta + \psi) \qquad \textit{(Equation 1)}$$

$$R_Y = M_Y + \left|\overrightarrow{MR}\right| \cos(\theta + \psi) \qquad \textit{(Equation 2)}$$

$$\left|\overrightarrow{MR}\right| = \sqrt{(R_X - M_X) + (R_Y - M_Y)}$$ *(Equation 3)*

where:

(M_X, M_Y) is the GPS measurement location in vehicle coordinates.
(R_X, R_Y) is the reference position in vehicle coordinates.
Θ is the angle defined by the vector $\overrightarrow{MR}$, measured clockwise in plan (top) view starting from an axis parallel to the vehicle X-axis.
Ψ is the vehicle heading angle.

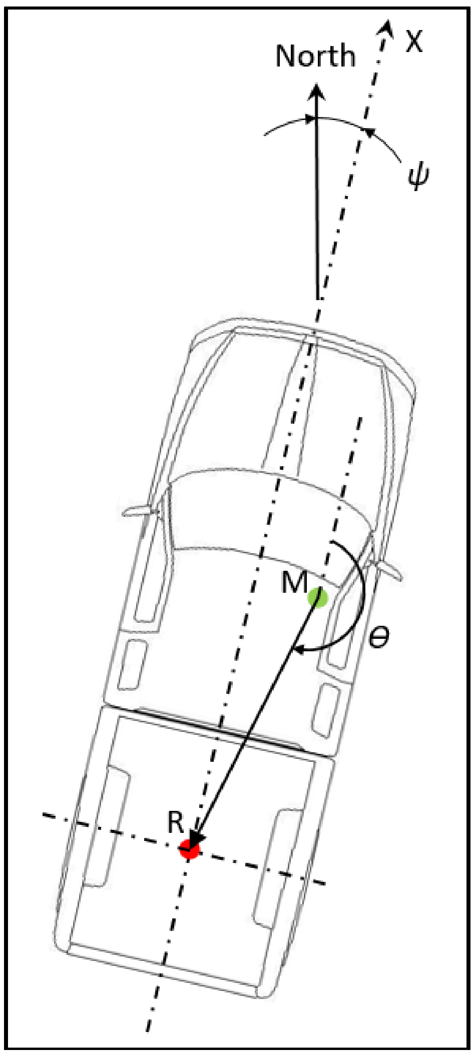

Figure 1. Vehicle reference point, GPS data translated to midpoint of rear axle centerline.

4.2.2 Leader's Path.

The leader's path, as shown in Figure 2, is defined as the curvilinear locus of position data traversed by the leader's reference position prior to the time of interest (of the follower). Certain conditions may disqualify data points, including any path that occurs when the leader travels in reverse (leading to a necessary change in course) and any path segment replaced by the leader continuing forward after traveling in reverse.

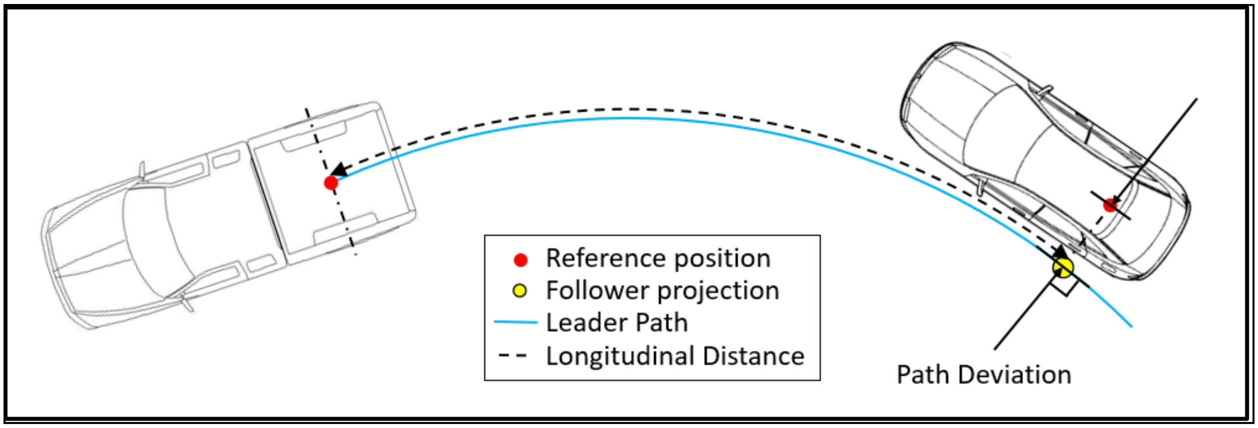

Figure 2. Gap distance and path deviation.

4.2.3 Gap Distance.

For a given follower, longitudinal distance (see Figure 2) represents the curvilinear distance traveled by the leader from the follower's current position. The longitudinal distance between two followers is then the difference of their respective longitudinal distances to the leader. To calculate gap distance, or the distance from the rear of a preceding vehicle to the front of the next follower vehicle, subtract reference position offsets, as shown in Figure 3.

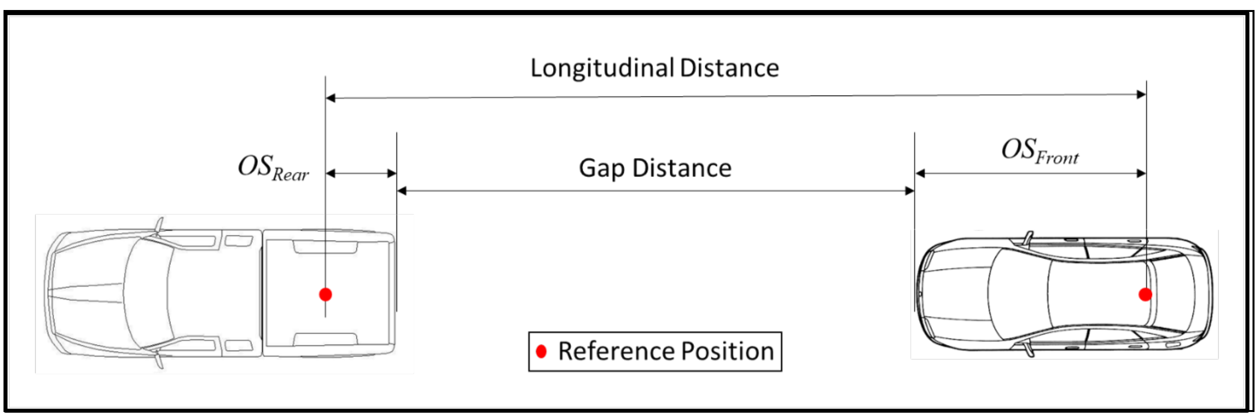

Figure 3. Gap distance calculation components.

4.2.4 Cross-track Error.

Cross-track error (or lateral path deviation) is defined as the lateral offset between the follower path and the path traversed by the leader at the current follower location, as shown in Figure 2.

4.3 Gap Distance and Cross-track Error Tests.

a. Conduct gap distance and cross-track error tests over a variety of terrains, environmental conditions, and speeds, based on guidance provided in the Detailed Test Plan (DTP). The SUT ODD may provide additional guidance and limitations for terrain, condition, and speed selection. When possible, include straight and curved paths, as well as level, inclined (ascending and descending) and hilly paths, over primary road, trail and cross-country terrains. Use of environmental conditions that include mud, dust, rain, snow, and nearby foliage are recommended, since they affect vehicle motion resistance and sensor performance. Ensure that additional safety precautions are taken as necessary while testing in adverse conditions.

b. Record leader and follower RTK GPS positional data and other relevant data sources listed in paragraph 2.2 while the vehicles traverse the various terrains. Report any visual or operational irregularities that occur during the course of testing for later correlation to test data and safety assessments.

4.4 Data Analysis.

a. Calculate gap and cross-track error distances from the GPS data. RTK GPS data may be recorded using the World Geodetic System (WGS84) coordinate system (latitude and longitude angular units) or the Universal Transverse Mercator (UTM) coordinate system (northing and easting distance units based on 60 north-south zones). The following procedures are based on use of UTM coordinates. If WGS84 data are used, convert the data to UTM coordinates. Select a base UTM zone for computations. If the vehicles cross UTM zones during testing, correct discontinuities in the vehicle paths arithmetically as necessary.

b. Computations are described in terms of data vectors (i.e., n x 1 column vectors, where n denotes the number of elements that comprise the vector). A vector index refers to a location of an element within a vector (e.g., an index of 10 indicates the 10^{th} element within the vector).

4.4.1 Create Leader and Follower Data Vectors.

a. From leader and follower UTM time-history data, create (n x 1) data vectors for time and X (easting) and Y (northing) Cartesian coordinates, where n is the number of discrete coordinate points in the data sample of interest. Translate the X and Y data to the vehicle reference points, as described in paragraph 4.2.1. Also, create a vector for leader distance traveled. If the leader reversed during the test, reduce the distance-traveled values appropriately.

b. Segment test files, when necessary, if files are large. Segments shall overlap sufficiently to include analysis between the leader and rear-most follower. It is recommended to use the distance traveled by the leader to define the segment windows and overlaps. Data recorded when all vehicles are stationary may be omitted.

c. Mathematically resample each vehicle's time and position data to the same time base, making the vectors the same size in each test segment.

4.4.2 Identify Data Not Valid for Analysis.

Follower positions are projected onto (or correlated to) the leader's path when determining cross-track error and gap distance. However, certain portions of the data may not be suitable for projection and analysis. Data to be omitted include, but are not limited to:

a. Follower position data recorded at the start of a test segment before a follower reaches the initial leader starting coordinates. The first valid follower data index has coordinates closest to the leaders starting coordinates.

b. Leader position data recorded on previous or subsequent laps around a given test area.

c. Leader position data recorded when reversing (e.g., prior to making a heading correction), shown as Path 2 in Figure 4. Generally, the leader reverses along its own path, but this is not always the case and may produce an irrelevant path for analysis.

d. The initial leader path replaced by the new leader path after resuming forward, shown as Path 1 in Figure 4. This path should be omitted only for data recorded after $T_{3,\text{ Leader}}$, since Path 1 could still be relevant for analysis when the entire convoy reverses with the leader.

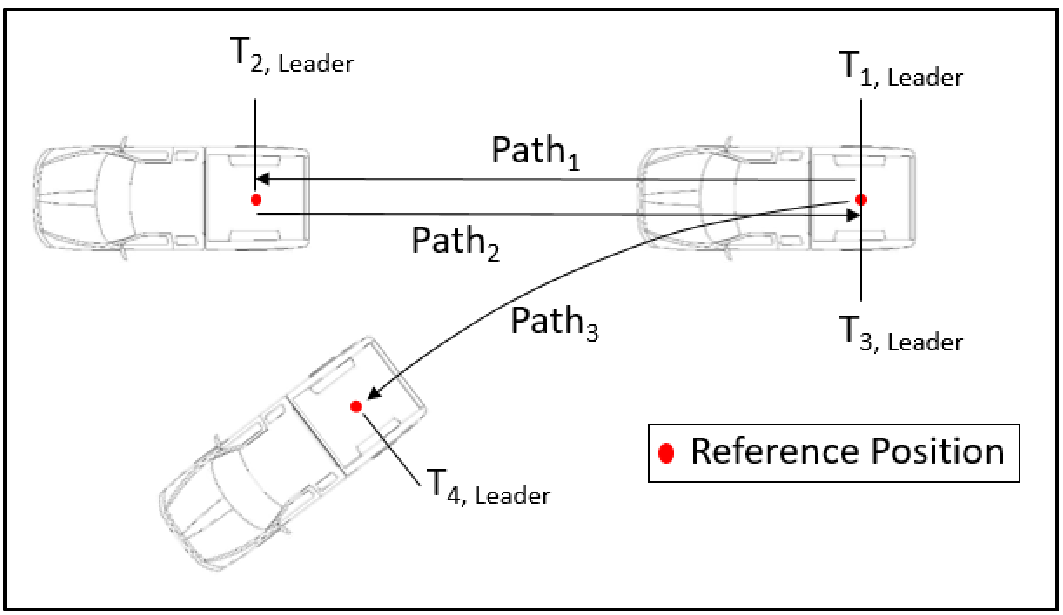

Figure 4. Leader heading correction event.

e. To simplify omission of coordinate data from analysis, it is recommended to replace the unwanted leader and follower path coordinates (X and Y) with a non-number value (such as ‘Not a Number’, or NaN used in MATLAB). In doing so, these values will automatically not be considered when projecting the follower position onto the leader path.

4.4.3 <u>Calculate Gap Distance and Cross-track Error</u>.

a. For each follower X and Y coordinate pair (X_F, Y_F), compute the distance to each leader X and Y coordinate pair using Equation 4, saving the results as a temporary distance vector. The process is shown graphically in Figure 5.

$$Distance\ (D) = \sqrt{(X_F - X_L)^2 + (Y_F - Y_L)^2} \qquad \textit{(Equation 4)}$$

where F indices represent the follower and L indices represent the leader.

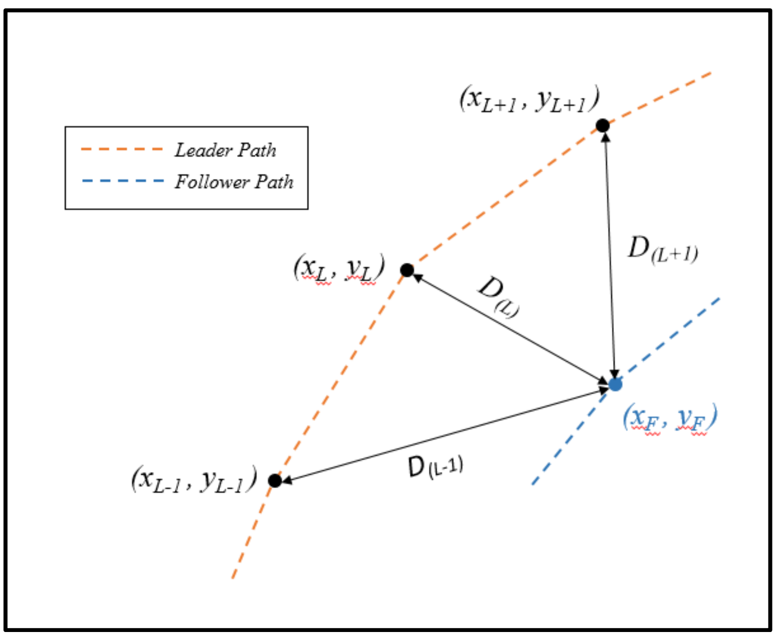

Figure 5. Identifying smallest distance.

b. Use the temporary distance vector index with the smallest value to identify the leader coordinate pair (X_L, Y_L) closest to the follower coordinate pair (X_F, Y_F). Also identify the preceding leader coordinate pair (X_{L-1}, Y_{L-1}) and following leader coordinate pair (X_{L+1}, Y_{L+1}).

c. Using Equation 5, calculate cross-track error (XTE) from each follower coordinate pair (X_F, Y_F) to the smoothed path connecting leader coordinates (X_{L-1}, Y_{L-1}) and (X_{L+1}, Y_{L+1}).

Figure 6 illustrates the process. This step is required because the leader's path is not measured continuously, but is discretized at a finite sampling frequency.

$$XTE = \frac{((x_{L+1}-x_{L-1})(y_{L-1}-y_F)-(y_{L+1}-y_{L-1})(x_{L-1}-x_F))}{\sqrt{(x_{L+1}-x_{L-1})^2+(y_{L+1}-y_{L-1})^2}} \quad \text{(Equation 5)}$$

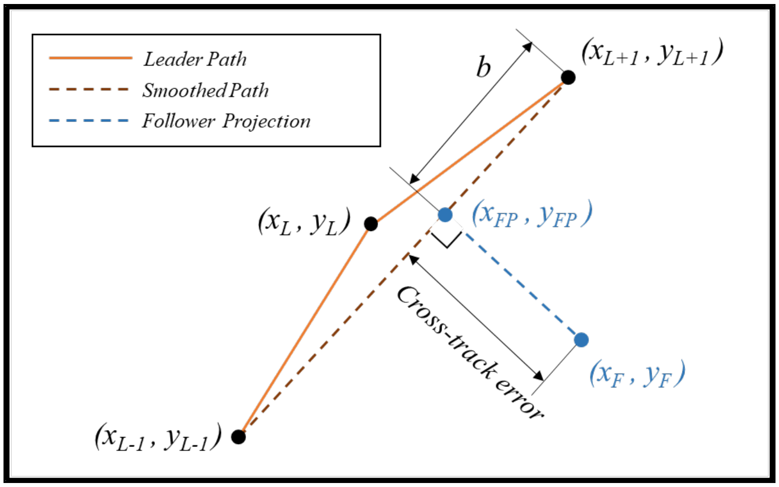

Figure 6. Cross-track error calculation.

Note: The point (X_{FP}, Y_{FP}) in Figure 6 does not fall directly on the line connecting two consecutive position coordinates. The effect is exaggerated by the figure. As a check on data quality, the angle between the 5-Hz measured data and the line defined by (x_{L-1}, y_{L-1}) and (x_{L+1}, y_{L+1}) can be calculated using their vector dot-products and tested against a maximum threshold.

d. Calculate the gap distance offset b (shown in Figure 5) for each follower coordinate (X_F, Y_F) using Equation 6.

$$b = \sqrt{(x_{L+1}-x_F)^2 + (y_{L+1}-y_F)^2 - LD^2} \quad \text{(Equation 6)}$$

e. For each follower coordinate (X_F, Y_F) and corresponding time t_F, calculate the curvilinear longitudinal distance traversed by the leader from (X_{FP}, Y_{FP}) to the leader coordinates at time t_F, using the leader distance traveled vector. Calculate the distance using Equation 7.

$$LongD = \left(\sum_{i=n(L+1)}^{n(t_F)} \sqrt{(x_{i+1}-x_i)^2+(y_{i+1}-y_i)^2}\right) + b \quad \text{(Equation 7)}$$

where:

$n_{(L+1)}$ denotes the leader index value at coordinate (X_{L+1}, Y_{L+1}).
$n_{(t_F)}$ denotes the leader index value at t_F..

f. Calculate *LongD* for each vehicle. Determine *LongD* between successive follower vehicles by subtracting the *LongD* from the preceding follower to the leader.

g. Calculate Gap Distance for each follower vehicle from *LongD* and the vehicle offsets shown in Figure 3. Repeat for each follower vehicle.

4.4.4 Analysis Recommendations.

The procedures outlined in paragraphs 4.4.3.a and 4.4.3.b are accomplished using numerical computing software. The procedures may be applied to each follower position sequentially, using a programmatic loop containing logical tests and numeric calculations. However, use of a programmatic loop requires considerable computing time, as functions contained within the loop are executed thousands of times. Analysis time is reduced significantly using the matrix technique described below and executed using MATLAB software (or similar).

a. Manipulate the leader's X, Y, time, and distance traveled data into row vectors and duplicate the rows once for every element in the follower's time-history (n times), creating four leader matrices. Similarly, manipulate the follower's data into column vectors and duplicate the columns once for every element in the leader's time history (m times), creating four follower matrices. The resulting leader and follower matrices have the same size (n x m). This technique is shown graphically for the leader and follower X values in Figure 7.

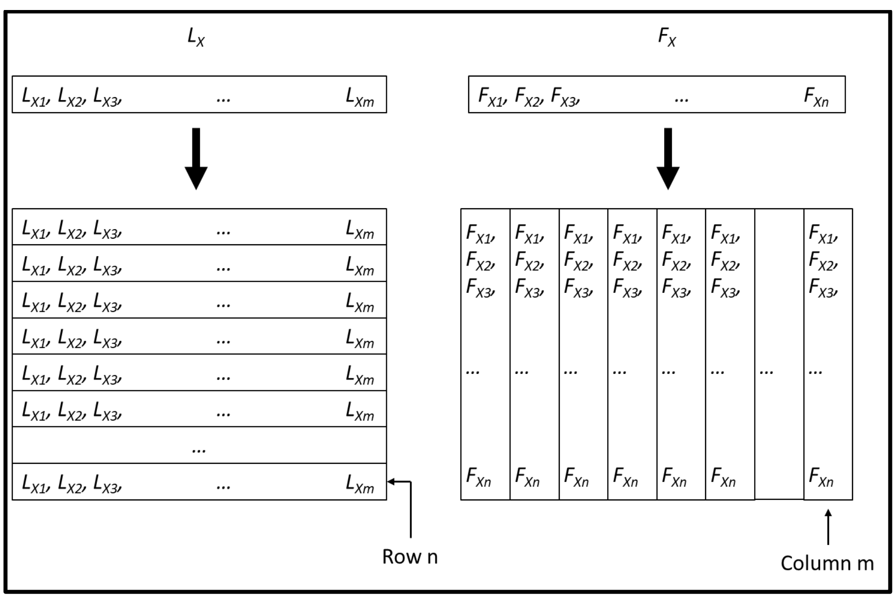

Figure 7. Vector manipulation into matrices.

b. Calculate the distance from every follower position to every leader position in the dataset using Equation 4 with the L_X, L_Y, F_X, and F_Y matrices. Using element-wise arithmetic operators (known as array operators in MATLAB), generate a matrix of point-to-point distances. A graphical representation of the resulting distance matrix for an example dataset is shown in Figure 8.

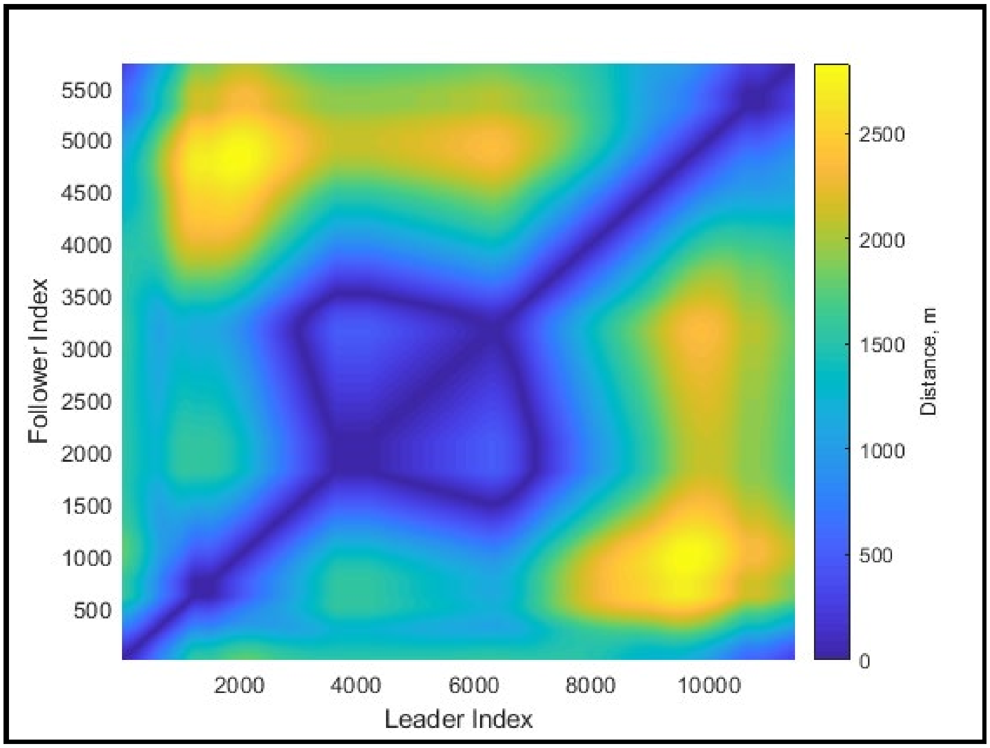

Figure 8. Point-to-point distance matrix.

c. Omit data identified in paragraph 4.4.2 as not valid for analysis by creating a logical index for each condition (a matrix of logical values that is true where a condition is met). Convert distances in the distance matrix to a non-number value (e.g., NaN) where the logical index is true. Figure 9 shows the resulting distance matrix with the omitted values. Note that the plot was re-scaled, since the resulting distance matrix only includes portions of the leaders path that are much closer to the follower.

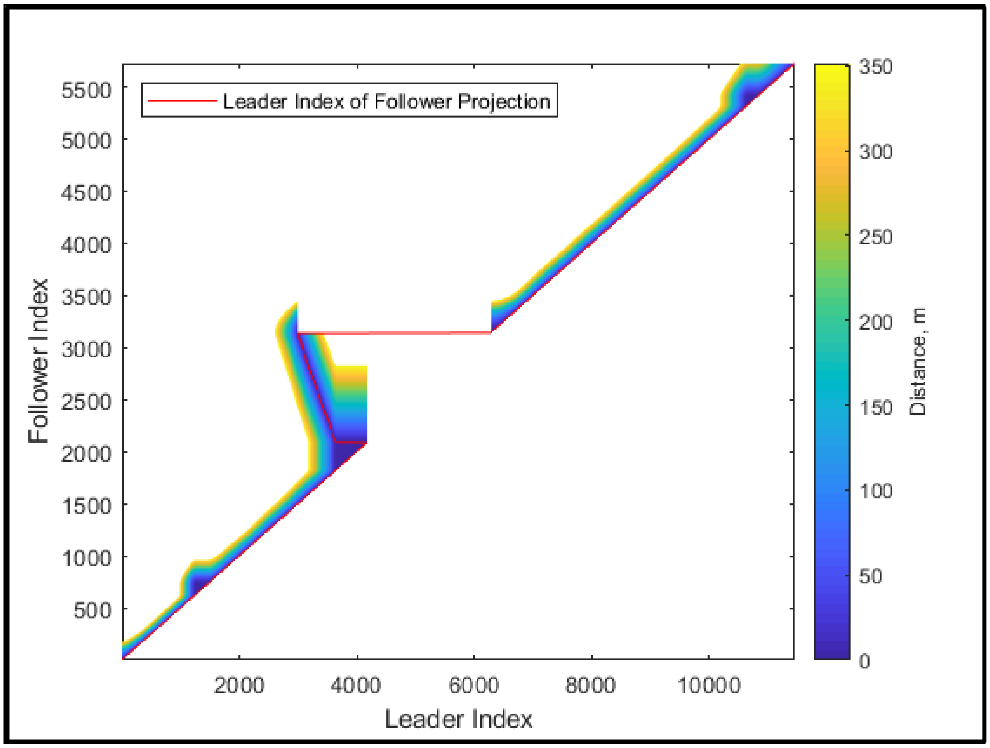

Figure 9. Reduced point-to-point distance matrix.

d. With only valid elements remaining in the distance matrix, identify the index in each column with the smallest distance value and create an associated index vector (having the length of the columns). The resulting index vector identifies the leader positions (X_L, Y_L) closest to the follower positions (X_F, Y_F). Execute the procedures outlined in paragraphs 4.4.3.c through 4.4.3.g as previously described.

5. DATA REQUIRED.

5.1 General Vehicle and Test Preparation.

a. Date and time of each test event.

b. Vehicle information: type (model), manufacturer and specific identification number.

c. Vehicle configuration: weight, length, width, height (including payload and/or trailer), load distribution, mileage, driveline configuration, central tire inflation system setting, operating mode for each scenario, and states of other Advanced Driver Assistance-Systems on the vehicles.

d. Description of test site (including environmental conditions and surrounding RF conditions).

e. Instrumentation name/type, manufacturer, identification (serial number, part number, etc.), calibration information, and location on vehicle (including photographs).

f. Location of GPS antennas on all SUT's.

g. Vehicle software versions for all subsystems (if applicable).

h. Vehicle hardware versions (if applicable).

i. Gap setting, (time or distance based).

j. Maximum/minimum convoy speed settings.

k. Maximum follower catch-up speed setting.

l. Target test speeds.

5.2 Gap Distance and Cross-track Error Measurements.

a. Vehicle direction of travel (forward/reverse).

b. Road incline gradient values.

c. Road curvature and direction.

d. Terrain type.

e. GPS data, including RTK corrections broadcast to the test site and/or recorded by instrumentation.

f. CAN bus data, as applicable.

g. Radio statistics data, as applicable.

h. Vehicle IMU data (X, Y, and Z accelerations and pitch, roll, and yaw rates), as applicable.

i. Onboard camera data, as applicable.

j. Radio frequency environment data, as applicable.

6. PRESENTATION OF DATA.

6.1 General Vehicle and Test Preparation.

Presented data in narrative, tabular, graphical, pictorial or other format, as appropriate.

6.2 Gap Distance.

a. Present gap distance statistics in terms of distance or time, as required in the DTP. Table 1 shows an example table header. Include a description of course and environmental conditions with the results.

TABLE 1. EXAMPLE GAP DISTANCE TABLE HEADER

		Measured Gap Distance Statistics				
Convoy Speed	Gap Setting	Lowest	25th Percentile	Median	75th Percentile	Highest
km/h	m	m	m	m	m	m

b. When applicable, present graphical summaries of gap distance results, showing the UGVs traversing test courses, as illustrated in Figure 10.

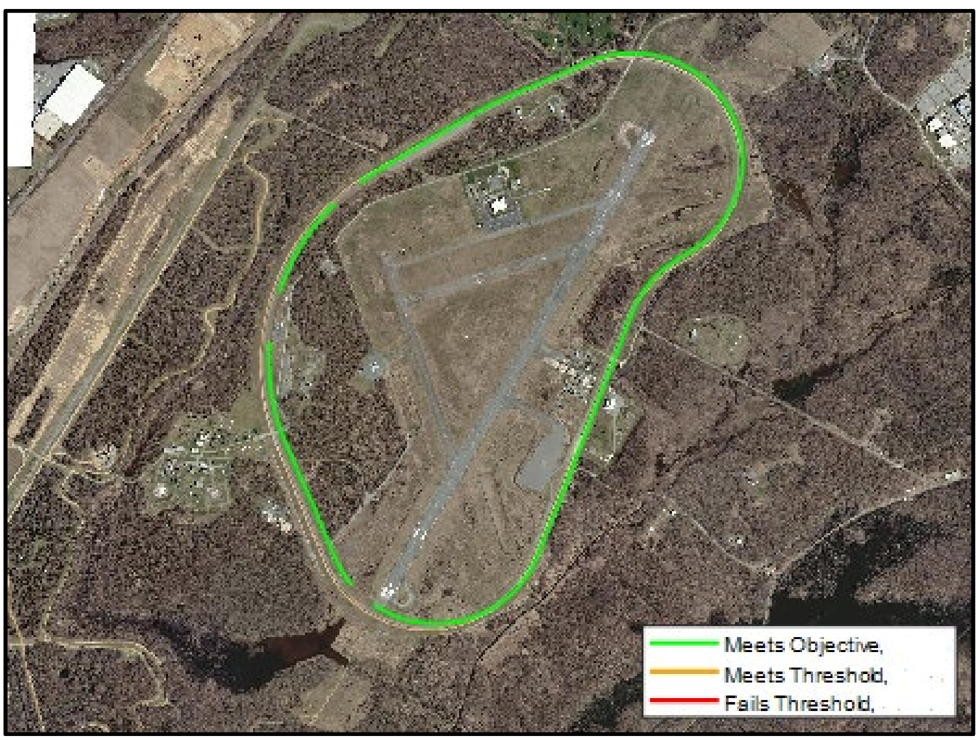

Figure 10. Example plot of gap distance results around a test course.

6.3 Cross-track Error.

a. Present cross-track error statistics, as required in the DTP. Table 2 shows an example table header. Include a description of course and environmental conditions with the results.

TABLE 2. EXAMPLE CROSS-TRACK ERROR TABLE HEADER

Convoy Speed	Gap Setting	Measured Cross-track Error Statistics				
		Highest Left of Follower	25th Percentile (Left of Median)	Median	75th Percentile (Right of Median)	Highest Right of Follower
km/h	s	cm	cm	cm	cm	cm

b. When applicable, present graphical cross-track error results, as shown in Figure 11. Box and whiskers plots represent the median (red), 25^{th} and 75^{th} percentiles (blue) and minimum and maximum (black) values of cross-track error.

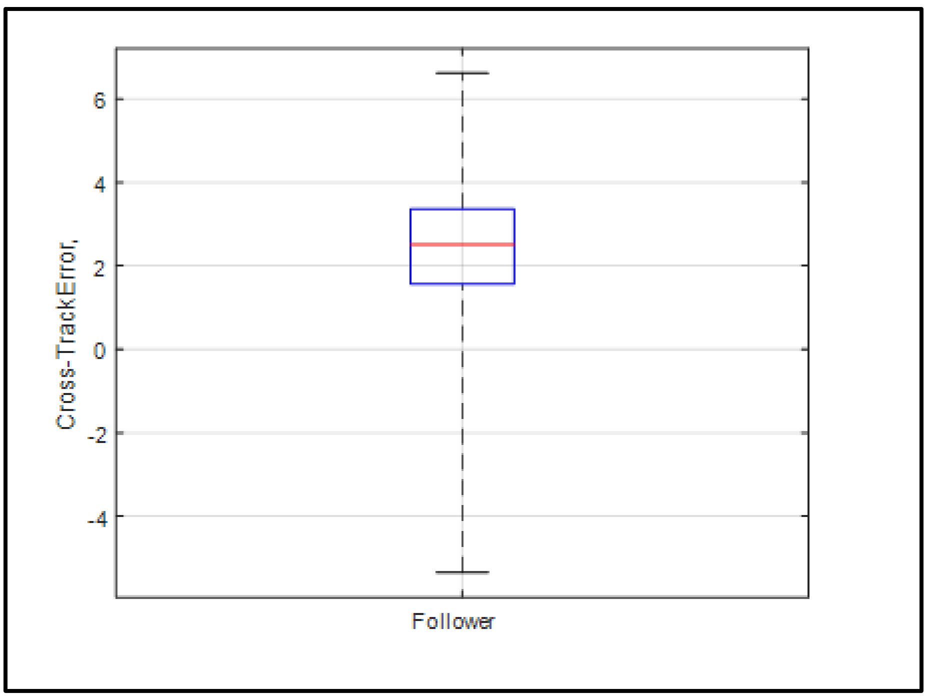

Figure 11. Example box and whisker plot of cross-track error results.

c. When applicable, present plots of follower cross-track error around a test course, similar to Figure 10.

(This page is intentionally blank.)

APPENDIX A. ABBREVIATIONS.

ABS	Anti-lock Brake System
ACC	Adaptive Cruise Control
ATEC	U.S. Army Test and Evaluation Command
°C	degrees Celsius
CAN	Controller Area Network
cm	centimeter
DTIC	Defense Technical Information Center
DTP	Detailed Test Plan
ESC	Electronic Stability Control
°F	degrees Fahrenheit
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
Hz	Hertz
IMU	inertial measurement unit
in.	inch
ISO	International Organization for Standardization
km/h	kilometers per hour
LIDAR	Light Detection and Ranging
LOS	line-of-sight
m/s	meters per second
mph	miles per hour
NLOS	non-line-of-sight
ODD	Operational Design Domain
RF	radio frequency
RTK	Real Time Kinematic
6-DOF	six degree of freedom
SOP	standard operating procedure
SUT	System Under Test

APPENDIX A. ABBREVIATIONS.

TOP	Test Operations Procedure
UGV	Unmanned Ground Vehicle
UTM	Universal Transverse Mercator
V2V	vehicle-to-vehicle
XTE	Cross-Track Error

APPENDIX B. REFERENCES.

1. SAE International Surface Vehicle Information Report J3016 Taxonomy and Definitions for Terms Related to On-Road Motor Vehicle Automated Driving Systems, January 2014.

2. TOP 01-2-506 Use of Controller Area Network (CAN) Data to Support Performance Testing, 16 July 2015.

3. ISO 15622 Intelligent transport systems- Adaptive cruise control systems- Performance requirements and test procedures, September 2018.

4. ISO 22839 Intelligent transport systems- Forward vehicle collision mitigation systems- Operation, performance, and verification requirements, June 2013.

5. SAE International Surface Vehicle Recommended Practice J2399 Adaptive Cruise Control (ACC) Operating Characteristics and User Interface, September 2014.

6. SAE International Surface Vehicle Recommended Practice J3029 Forward Collision Warning and Mitigation Vehicle Test Procedure (Truck and Bus), October 2015.

7. SAE International Surface Vehicle Information Report J3063 Active Safety Systems Terms and Definitions, November 2015.

8. TOP 02-2-002A Steering and Cornering Behavior, 25 September 2019.

9. TOP 02-2-608 Braking, Wheeled Vehicles, 20 May 2008.

10. TOP 02-2-718A Electronic Stability Control, 1 October 2018.

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

12. TOP 02-2-543 Line-of-Sight/Non-Line-of-Sight (LOS/NLOS) Testing of Unmanned Ground Vehicle (UGV) Systems, 24 November 2008.

(This page is intentionally blank.)

APPENDIX C. APPROVAL AUTHORITY.

CSTE-CI 3 February 2022

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 02-2-548, Leader-Follower Unmanned Ground Vehicle (UGV) Gap Distance and Lateral Deviation Measurements

1. Test Operations Procedure (TOP) 02-2-548, Leader-Follower Unmanned Ground Vehicle (UGV) Gap Distance and Lateral Deviation Measurements, 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 procedures for measuring the longitudinal and lateral path-following performance of Unmanned Ground Vehicle follower vehicle(s) traversing a path defined by a lead vehicle.

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.

GWYNN.ROSS.A.1266313965 Digitally signed by GWYNN.ROSS.A.1266313965 Date: 2022.02.03 14:48:54 -05'00'

MICHAEL J. ZWIEBEL
Director, Directorate for Capabilities Integration (DCI)

(This page is intentionally blank.)

Forward comments, recommended changes, or any pertinent data which may be of use in improving this publication to the following address: Policy and Standardization Division (CSTE-CI-P), U.S. Army Test and Evaluation Command, 6617 Aberdeen Boulevard, Aberdeen Proving Ground, Maryland 21005-5001. Technical information may be obtained from the preparing activity: Unmanned Vehicle Test Division, Automotive Directorate (TEDT-AT-AD-U), U.S. Army Aberdeen Test Center, 400 Colleran Road, Aberdeen Proving Ground, Maryland 21005-5059. Additional copies can be requested through the following website: https://www.atec.army.mil/publications/documents.html, or through the Defense Technical Information Center, 8725 John J. Kingman Rd., STE 0944, Fort Belvoir, VA 22060-6218. This document is identified by the accession number (AD No.) printed on the first page.