

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

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1. REPORT DATE (DD-MM-YYYY) 25-09-2019		2. REPORT TYPE Final		3. DATES COVERED (From - To)	
4. TITLE AND SUBTITLE Test Operations Procedure (TOP) 02-2-002A Steering and Cornering Behavior			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 Instrumentation Division (TEAT-ADI) U.S. Army Aberdeen Test Center 6943 Collieran Road Aberdeen Proving Ground, MD 21005-5059				8. PERFORMING ORGANIZATION REPORT NUMBER TOP 02-2-002A	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) Policy and Standardization Division (CSTE-CI-P) U.S. Army Test and Evaluation Command 6617 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 Defense Technical Information Center (DTIC), AD No.: This TOP supersedes TOP 02-2-002 Dynamic Stability, Handling and Steering, dated 19 May 2009, and TOP 02-2-609 Steering, dated 18 July 1980. Marginal notations are not used in this revision to identify changes, with respect to the previous issue, due to the extent of the changes.					
14. ABSTRACT This TOP prescribes procedures for analyzing the steering and cornering behavior of vehicles and vehicle combinations. The tests described encompass turn ability, maneuverability, response to steady-state and transient steer inputs, handling, directional stability, roll stability, vehicle controllability, accident avoidance maneuver performance, and electronic stability control (ESC) systems. Pertinent automotive industry standards are referenced for terminology and test methods.					
15. SUBJECT TERMS Steering and Handling, Stability, Control, Response, Maneuverability, Geometric Stability Ratio, Static Rollover Threshold, Tilt Table, Cramping Angle, Steering Ratio, Steering Effort, Turning, Off-tracking, Slalom, Entry Control Point, Pivot Steering, Drift, Self-Steer During Braking, On-Center Handling, Overall Steering Performance, Steady-State Circular Test, Response Gain, Transient Response, Emergency Lane Change, Electronic Stability Control, Lateral Stability, Roadway Simulator, Dead-Engine Steering					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT SAR	18. NUMBER OF PAGES 81	19a. NAME OF RESPONSIBLE PERSON
a. REPORT Unclassified	B. ABSTRACT Unclassified	C. THIS PAGE Unclassified			19b. TELEPHONE NUMBER (include area code)

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US ARMY TEST AND EVALUATION COMMAND
TEST OPERATIONS PROCEDURE

Test Operations Procedure 02-2-002A
DTIC AD No.

25 September 2019

STEERING AND CORNERING BEHAVIOR

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1. SCOPE.

a. Standardized tests are provided for analyzing vehicle steering and cornering behavior. The associated tests, listed in Table 1, are categorized in terms of basic measurements, static stability, steering and handling performance, and dynamic stability and control.

TABLE 1. STEERING AND CORNERING BEHAVIOR SUBTESTS

ASSESSMENT CATEGORY	SUBTEST	REFERENCE STANDARDS (Appendix M)	VEHICLE APPLICATION
Basic Measurements	General Vehicle Characterization	SAE J1574-1 ^{1**} , TOP 02-2-800 ² , TOP 02-2-801 ³ TOP 02-2-704A ⁴	Wheeled, tracked
Static Stability	Geometric Stability Ratio	SAE J670 ⁵	Wheeled
	Static Rollover Threshold (Tilt-Table)	SAE 2180 ⁶ ISO 16333 ⁷	Wheeled, tracked
Steering and Handling Performance	Cramping Angle and Steering Ratio	SAE J266 ⁸ , SAE J2181 ⁹	Wheeled
	Steering Effort (incl. Dead Engine Steering)	AVTP 03-60 ¹⁰	Wheeled, tracked
	Turning Circle Diameter	SAE J695 ¹¹	Wheeled, tracked
	Minimum Road Width	AVTP 03-60	Wheeled, tracked
	Off-tracking (including Swept Paths)	SAE J695	Wheeled
	Slalom	AVTP 03-60	Wheeled, tracked
	Entry Control Point Maneuverability	TM 5-853-2 ¹²	Wheeled, tracked
	Pivot Steering	AVTP 03-60	Wheeled, tracked
	Drift		Wheeled, tracked
	Self-Steer During Braking		Wheeled
	On-Center Handling	TOP 02-2-600 ¹³ , ISO 13674-1 ¹⁴ , ISO 13674-2 ¹⁵ , ISO 11012 ¹⁶	Wheeled
	Handling	SAE J1441 ¹⁷	Wheeled, tracked
Overall Steering Performance		Wheeled, tracked	

** Superscript numbers correspond to Appendix N, References.

TABLE 1. CONTINUED

ASSESSMENT CATEGORY	SUBTEST	REFERENCE STANDARDS (Appendix M)	VEHICLE APPLICATION
Dynamic Stability and Control	Steady State Circular Steer	SAE J266, SAE J2181, ISO 4138 ¹⁸ , ISO 14792 ¹⁹	Wheeled
	Response Gain	SAE J266	Wheeled
	Transient Response	ISO 7401 ²⁰	Wheeled
	Emergency Lane Change	AVTP 03-160W ²¹	Wheeled
	Electronic Stability Control	TOP 02-2-718A ²²	Wheeled
	Lateral Stability of Vehicle Combinations	ISO 14791 ²³	Wheeled
	Control on Adverse Terrain		Wheeled, tracked
	Control on Side Slopes	TOP 02-2-610 ²⁴	Wheeled, tracked

SAE = SAE International (Formerly Society of Automotive Engineers)
 ISO = International Organization for Standardization
 TOP = Test Operations Procedure
 AVTP = Allied Vehicle Testing Publication
 TM = Army Technical Manual

b. This TOP utilizes terminology documented in SAE International Recommended Practice J670, Vehicle Dynamics Terminology, and ISO 8855²⁵, Road vehicles-Vehicle dynamics and road holding ability-Vocabulary. When possible, automotive industry test standards from SAE International and ISO were used.

1.1 Purpose.

a. Loss of vehicle control, loss of directional stability, or exceeding rollover limits when operating a motor vehicle can result in serious personal injury and equipment damage. Also, insufficient turn ability can result in poor vehicle maneuverability. The purpose of this TOP is to provide standardized tests to assess the performance and safety of ground vehicles when steering and cornering. The tests described encompass:

- (1) Turn ability.
- (2) Maneuverability.
- (3) Response to steady-state and transient steer inputs.
- (4) Handling.
- (5) Directional stability (understeer/oversteer behavior).

- (6) Roll stability.
- (7) Vehicle controllability.
- (8) Accident avoidance maneuver performance.
- (9) Electronic stability control (ESC) systems.

b. These tests can be performed with the test vehicle operating on standard test courses or when positioned on Aberdeen Test Center's (ATC's) Roadway Simulator (RWS).

NOTE: As military vehicle speeds continue to increase, it becomes increasingly important to understand the interrelationships between directional stability (understeer/oversteer behavior), steering sensitivity, and roll stability.

1.2 Limitations.

This TOP applies to wheeled vehicles having at least two axles, vehicle combinations, and tracked vehicles, with an emphasis on military ground vehicles. These procedures may be used for both developmental and production vehicles.

2. FACILITIES AND INSTRUMENTATION.

2.1 Facilities.

<u>Item</u>	<u>Requirement</u>
Tilt Table	A singular continuous platform capable of tilting a test vehicle parallel to its longitudinal axis. The platform must remain essentially planar throughout testing.
Circular Test Course	Uniform hard surface of concrete or asphalt with a gradient of no more than 1% in any direction. Area must be of sufficient size to allow for a 30-meter (m)-radius circular road course; larger courses may be required for testing vehicles with multiple axles.
Lane Change Test Course	A straight asphalt or concrete roadway having a width of at least 15 m over a length of at least 200 m, with additional roadway leading to and from the test course to allow for entry at target test speeds and stopping after the maneuver.

Vehicle Dynamics Test Area	A generic flat asphalt or concrete roadway with a gradient of no more than 2.5% (in general) in any direction and dimensions sufficient for the required test. Some tests described in this TOP may require a gradient no more than 1% in the lateral direction. Pertinent standards should be referenced.
Roadway Simulator	A dynamic vehicle-in-the-loop test machine that utilizes D’Alembert’s principle and kinematic relationships for operation. It consists of a series of treadmills positioned beneath the vehicle tires, an instrumented vehicle restraint system, an autopilot robotic driver, a hydraulic power supply, and a system controller.
Steering Performance Course	Composed of selected Munson Test Area courses such as those located at ATC. See paragraph 4.15 for additional details.
Side slope test courses	Paved 20-, 30-, and 40-percent slopes.
Adverse terrain courses	Sand course, abrasive mud course, wave course, staggered bump course, or other courses as required, described in TOP 01-1-011B ²⁶ .

2.2 Instrumentation.

The measuring and recording equipment shall be applied in accordance with ISO 15037-1²⁷, Road vehicles- Vehicle dynamics test methods- Part 1: General Conditions for Passenger Cars (which included light trucks) or ISO 15037-2²⁸, Road vehicles- Vehicle dynamics test methods- Part 2: General Conditions for Heavy Vehicles and Buses, unless indicated otherwise below or as noted in a referenced test standard or TOP.

<u>Devices for Measuring</u>	<u>Recommended Maximum Error of Combined System</u>
Steering wheel angle	±0.5 degree
Yaw velocity (rate)	±0.1 degrees per second (deg/sec)
Turning diameter	1% of value
Distance measuring device	1% of value

2.3 Specialized Equipment.

Specialized equipment and instrumentation required for vehicle preparation, test course set-up, test control, and test observation are as follows:

- a. Safety device with supporting structures on either side of the vehicle (outriggers) to prevent rollover. The outriggers must be designed and installed in such a manner that the vehicle test weight, center of gravity (CG), and moment of inertia remain as unchanged as practical (objective – outrigger weight \leq 10-percent of vehicle test weight).
- b. Traffic cones or other means of marking the test course lanes.
- c. Video camera (to observe wheel lift and overall vehicle behavior).
- d. Steering-wheel angle and torque measuring device. An instrument attached to the test vehicle's steering wheel (or installed in place of the steering wheel in some cases) that is calibrated to measure the steering effort (torque) exerted on the steering wheel and the steering wheel angle during turning maneuvers.
- e. Non-contact fifth wheel sensor. An instrument used for measuring both the vehicle longitudinal and lateral velocities simultaneously that are required for the calculation of vehicle sideslip angles.
- f. Steering robot device. An automatic control device used to provide objective and precise steering maneuvers during testing. An example is shown in Figure 1. The device can be triggered at specific vehicle speeds and dynamic rate conditions (e.g., roll rate), and is operated by the vehicle driver. The device also measures steering wheel angle and steering torque.



Figure 1. Steering robot device.

g. Inertial Measurement Unit (IMU). An instrument used for measuring vehicle longitudinal, lateral, and vertical accelerations and pitch, roll, and yaw velocities. The unit may also measure vehicle pitch, roll, and yaw angles, and correct acceleration and rate measurements based on the angle data. The unit is mounted in the vehicle near the center of gravity with its axes parallel to the vehicle X_v , Y_v , and Z_v axes, in accordance with SAE International J670.

3. REQUIRED TEST CONDITIONS.

It is recommended that ISO 15037-1 Part 1, or ISO 15037-2 Part 2 (depending on the class of vehicle under test) be used as a guide for:

- a. Variables to be measured.
- b. Measuring equipment and data processing.
- c. Environment (test track and wind velocity).
- d. Test vehicle preparation.
- e. Initial driving (vehicle and tire warm-up).
- f. Test reporting (general data and test conditions).

3.1 Additional Preparation For Test.

- a. Obtain copies and review the referenced SAE International, ISO and AVTP test procedures.
- b. Record vehicle position measurements (X_v , Y_v , and Z_v coordinates) of the IMU, non-contact fifth wheel sensor (for velocity and sideslip measurements), and roll angle sensors (other than the IMU) for later data processing.
- c. Prepare data collection sheets to record all pre-test information, conditions of test, test results, observations, and measurements that would be valuable for analysis and assessment.
- d. Review all pertinent instructional material issued with the test vehicle by the manufacturer, contractor, or government, as well as reports of previous similar tests on the same types of vehicles.
- e. Ensure that all test personnel are familiar with the required technical and operational characteristics of the item and with the required test procedures.

3.2 Additional Test Controls.

- a. Prior to the initiation of testing ensure that:

(1) The vehicle has been prepared and equipped in accordance with standard use and/or within the specifications presented in the test plan.

(2) The vehicle is payloaded in accordance with the test plan.

(3) The vehicle has received the proper break-in operation.

(4) If vehicle stability is a concern, rollover protection (outriggers) must be used unless the testing agency's Standard Operating Procedures (SOP) assures both of the following conditions are met:

(a) Calculations of the maximum lateral acceleration necessary for the system to perform the required testing throughout the anticipated speed range demonstrate that the system is safely below the stability limit measured during the tilt table test. An increase in lateral acceleration due to potential oversteer should be considered.

(b) The test agency commander or technical director has provided a waiver to allow testing without outriggers.

b. The peak friction coefficient of each test track must meet the requirements of the procedural documents. The peak friction coefficient (also known as the peak braking coefficient) will be determined in accordance with American Society for Testing and Materials (ASTM) E1337-90²⁹, Standard Test Method for Determining Longitudinal Peak Braking Coefficient of Paved Surfaces Using Standard Reference Test Tire.

3.3 Restrictions.

a. Tests are not conducted at night, during inclement weather, or when the road surface may introduce a hazard to the test vehicle or other traffic on the road. Dry, un-obstructed surfaces are used unless the test plan introduces a specific requirement. Local safety and operational procedures will be carefully followed. Desirable environmental conditions for test conduct are as follow:

(1) Wind speed: ≤ 5 meters per second (m/s) average value.

(2) Ambient temperature: $0 \leq T \leq 30$ °Celsius (°C).

b. Ambient conditions at the time of testing shall be recorded.

4. TEST PROCEDURES.

4.1 General Vehicle Characterization.

a. Many factors affect the results of the performance tests described herein, including vehicle payload configuration, weight distribution, center of gravity location, tire

selection/condition, wheel alignment, steering system condition, and suspension/damper condition. At a minimum, the following information shall be reported with the test results.

- (1) Vehicle identification.
- (2) Odometer mileage.
- (3) Vehicle payload condition (amount of payload and location).
- (4) Wheelbase and track.
- (5) Vehicle weight distribution.
- (6) Vehicle center of gravity location.
- (7) Tire selection, condition, and tread depth (see TOP 02-2-704A).
- (8) Suspension configuration (highway, off-road, etc.) and suspension or vehicle trim heights.
- (9) Drivetrain configuration (2x4, 4x4, driveline locks, etc.).
- (10) Suspension and steering system condition.

b. It is recommended that SAE International J1574-1 be used as a guide to more thoroughly document the configuration and condition of the test vehicle.

4.2 Geometric Stability Ratio.

a. The Geometric Stability Ratio provides a first-order estimate of the rollover threshold due to lateral acceleration during steady-state cornering. The Static Stability Factor (SSF), which is the Geometric Stability Ratio at a load condition consisting of curb weight plus a 50th percentile male (161.4 pound) driver, may be used alternatively for passenger vehicles and light trucks.

b. Calculate and record the Geometric Stability Ratio, as defined in SAE International J670 (Equation 1).

$$\text{Geometric Stability Ratio (units of } g) = T/2H \quad (\text{Equation 1})$$

where:

T = average vehicle track

H = center of gravity height, above the ground

Note: The Geometric Stability Ratio should not be used as an accurate indicator of true steady-state or dynamic cornering rollover limits, since it does not account for tire and vehicle

compliances or dynamic effects. The ratio yields a higher rollover threshold than would be observed during real cornering. For example, a vehicle with a Geometric Stability Ratio of 0.95 g may actually rollover during a steady-state cornering maneuver at 0.70 g. The ratio is best used as a relative measure to compare the rollover propensity of different vehicles or different payload configurations.

4.3 Static Rollover Threshold (Tilt-table).

A test vehicle's static rollover threshold and maximum side slope angle are determined by tilting a vehicle about its longitudinal axis (on a tilt-table platform) until multiple upside wheels lift from the plane of the platform. The tangent of the tilt table inclination angle at the point of wheel lift determines the threshold (Equation 2).

$$a_y \text{ (units of } g) = \tan \emptyset \quad \text{(Equation 2)}$$

where:

a_y = lateral acceleration threshold

\emptyset = platform tilt angle (degrees or radians)

- a. The tilt table test is conducted in accordance with SAE International J2180.
- b. The test vehicle is positioned on the tilt table with appropriate safety straps attached to prevent rollover. The vehicle is then tilted about its roll axis until the uphill tires lift off the platform. ATC SOP 385-5175³⁰, Operations on the Automotive Tilt Table, provides important guidance for safe conduct of the test.
- c. Conduct the test with the vehicle positioned in both directions and at each of the configurations described in the test plan.
- d. The tilt table test shall be performed prior to high-speed test procedures.

Note: The Static Rollover Threshold provides a more accurate estimate of a vehicle's steady-state cornering rollover threshold than the Geometric Stability Ratio because tire and vehicle compliances are included. However, the static rollover threshold measurement generally yields a higher rollover threshold than would be observed during steady-state cornering. For example, a vehicle with a static rollover threshold of 0.78 g may actually rollover during a steady-state cornering maneuver at 0.70 g. Neither the Static Rollover Threshold or the Geometric Stability Ratio account for dynamic effects during transient cornering, and should not be used to establish the rollover threshold for dynamic maneuvers.

4.4 Cramping Angle And Steering Ratio.

4.4.1 General Comments.

a. Cramping angles are the maximum right and left wheel steering angles on an axle, and are limited by physical stops. The cramping angles, along with the wheelbase and track, determine the low-speed maneuverability limits of a vehicle.

b. Steering Ratio, defined in SAE International J670, is the rate of change of steering-wheel angle with respect to the mean reference steer angle of a pair of steered wheels at a given steering-wheel position. The mean reference steer angle is the average of the right and left wheel (reference) steer angles for a given steering-wheel angle. For a passive mechanical system, this relationship is defined by the kinematics of the steering system in the absence of suspension roll and tire forces and moments, but including static tire vertical load. This relationship is further defined with the vehicle at rest at a specified load condition, set of vehicle trim heights, or set of suspension trim heights. The reference steer angles, and hence the steering ratio, are typically non-constant and non-linear across the steering range.

c. For an actively controlled steering system, the kinematic relationship between steering-wheel angle and steer angle may be augmented by control logic that is a predefined function of steering-wheel angle. Where the programmed function varies with some condition such as vehicle speed, load condition, suspension trim heights, or other vehicle or environmental conditions, the relationship is specific for each unique set of conditions. If the factor(s) (e.g., vehicle speed) that modify the kinematic relationship between steering-wheel angle and steer angle in a predefined manner are known, the reference steer angle shall be determined at each state that is of interest.

d. Other factors that may be utilized by a control system in modifying the vehicle steer angle could include lateral acceleration, yaw velocity, roll angle, or other variables that are not a direct function of steering-wheel angle. These additional factors are not considered in the determination of reference steer angle, as they essentially act in the same manner as steering and suspension compliances and are therefore understeer/oversteer factors (see SAE International J670, Section 5.5.1.2).

e. In practice, it may not be possible to determine the reference steer angle when the steering control system is active. In such cases, the reference steer angle without automatic control inputs may be used as a baseline provided the automatic inputs can be shut off and the baseline condition is properly documented. For these cases, determination of understeer-oversteer gradient or Ackerman properties from the baseline reference steer angle is only meaningful for the case with the active control system disabled, and should be documented as such.

f. For a two-axle vehicle with front and rear-steerable axles, the Overall Steering Ratio is the rate of change of steering-wheel angle with respect to *included reference steer angle* at a given steering-wheel position. The included reference steer angle is the mean reference steer angle of the front axle minus the mean reference steer angle of the rear axle.

g. For vehicles with multiple front and/or rear steerable axles that all steer during high-speed cornering, the use of the Overall Steering ratio is not defined in SAE International or ISO standards. Therefore, with multiple front and/or rear steering axles, handling diagrams and understeer/oversteer gradients (see paragraph 4.16, Steady-State Circular Test) are not reported.

4.4.2 Cramping Angle Measurement.

a. Determine the maximum angle (i.e., cramping angle), relative to the vehicle centerline, through which the wheels of the steering axle(s) can be steered from the straight-ahead position to the maximum left and maximum right directions. Measurement is best accomplished using calibrated turn plates (frictionless bearing pads) beneath the steerable wheels, greased plates beneath the wheels, or on a kinematics and compliance (K&C) test rig.

b. For the maximum left position, measure the cramping angle at the left wheel; for the maximum right position, make the measurement at the right wheel.

c. Measure the steering-wheel angles, δ_{sw} , required to move the wheels from one extreme to the other (maximum left to maximum right or vice versa). This measurement is best accomplished with an analog or digital rotational encoder attached to the steering wheel or with a steering robot, but may be estimated with a protractor.

d. Check wheel stops or other limiting devices for their ability to positively limit the cramping angle to the maximum angle specified by the vehicle manufacturer.

Notes:

1. During testing, the road plane beneath each tire of the vehicle shall be at the same elevation above the ground plane, which may require the use of spacers.

2. The turn plates must allow for lateral and longitudinal translation of the wheels that may occur during steering, without constraining motion.

3. The vehicle body should be constrained to not move laterally during testing, unless the motion is measured and accounted for in analysis.

4.4.3 Steering Ratio Measurement.

The notes for cramping angle measurement apply to steering ratio measurement, as well.

a. Place the steered wheels of the vehicle on calibrated, frictionless turn plates (described in preceding section).

b. For vehicles equipped with tilt-steering, report the position of the steering column along with the steering ratio data obtained. If the steering column has both tilt and extension adjustments, it is recommended to test initially with the steering column in the middle tilt angle, middle extension position.

- c. Record the vehicle suspension setting (e.g., highway) and vehicle or suspension trim heights.
- d. Measure and record the steering wheel angle, δ_{SW} , and the angles of the right and left wheels, δ_{right} and δ_{left} , respectively, over the range of motion for which the steering ratio data will be used (e.g., steady-state circular test). A rotational (analog or digital) encoder is generally the best device used to measure the steering wheel angle. It is also recommended that analog or digital encoders be adapted to and used with the turn plates.
- e. Record measurements at small increments of the steering wheel over the target range of motion. If analog or digital encoders are used and continuously recorded with a digital data acquisition system, the steering wheel may be rotated continuously (but slowly, less than 50 deg/sec) over the range of motion in both steer directions. It is recommended that three full cycles, 3-1/2 if the steering is started from straight ahead, are measured for averaging of data.
- f. With tilt steering, it is recommended to repeat testing at the maximum tilt angle, maximum extension setting and the minimum tilt angle, minimum extension setting.

Note: The use of digital encoders on the steering wheel and turn plates allows small non-linear variations due to universal joint indexing and design to be observed. For very precise measurements of this nature, use of a steering robot may be necessary.

4.5 Steering Effort.

- a. Steering effort, or torque, is a measure of the effort required by the driver to affect a rotation of the steering-wheel with the vehicle stationary or moving. Steering effort may be measured to assess control force compliance with Military Standard (MIL-STD)-1472G CN1³¹, Department of Defense Design Criteria Standard, Human Engineering, but also has value when assessing handling, power-assist mechanical advantage, loss of power assist, steering feedback when approaching cornering limits, low-speed maneuvering, and steering from a parked condition.
- b. Steering effort is influenced by many design features of the vehicle, tire characteristics, and states of cornering, and is dependent on steering-wheel angle and steering rate when measured.

4.5.1 Vehicle Stationary- Engine Running.

- a. Install a calibrated steering-wheel angle and torque measuring device, or steering robot, on the steering wheel or in place of the steering wheel for testing. Record steering-wheel angle, δ_{SW} , and steering torque, M_{SW} , continuously with a digital data acquisition system for the duration of each test event.

Note: It is recommended to conduct testing with a steering robot for precise control of steering wheel speeds.

- b. Check and adjust tire pressures for the vehicle payload condition(s) to be tested.
- c. Warm up the vehicle by driving for at least 15 minutes, ensuring that the steering servo oil (if hydraulic assist is used) and engine coolant temperatures reach normal operating temperatures and are stabilized.
- d. Based on the steering cramping angles, select a steering-wheel angle range of interest, ensuring that the steering stops are not contacted during testing. Establish $\delta_{SWmax, right}$ and $\delta_{SWmax, left}$.
- e. Position the vehicle on a dry, flat test surface (< 1 percent slope) , preferably asphalt or concrete, with the transmission in neutral, at the pre-determined engine speed (e.g., normal idle or tactical idle), and with the vehicle brakes not applied. Wheel chocks can be applied to a non-steered axle for safety.
- f. Select an initial constant steering-wheel speed for testing based on the test plan. If no guidance is given, start with 5 deg/sec for passenger vehicles and 10 deg/sec for commercial and military vehicles.
- g. Starting from the straight forward position of the steering wheel, δ_{SWzero} , turn the steering wheel from δ_{SWzero} to $\delta_{SWmax, right}$ at the initial constant steering-wheel speed, then immediately to $\delta_{SWmax, left}$ at the same speed, and then immediately back to δ_{SWzero} at the same speed. The steering input is a triangular wave function.

Note: Maximum torque limits of the steering robot or the human operator may be exceeded before reaching $\delta_{SWmax, right}$ and $\delta_{SWmax, left}$ due to high axle weights associated with many military vehicles at the gross vehicle weight rating condition. To protect the steering robot, lower threshold torque limits may need to be programmed in the steering robot controller to avoid overloading the steering robot.

- h. Move the vehicle forward on the test surface a sufficient distance to perform additional tests on a clean contact patch and to avoid wearing or damaging the surface from excessive use. Place the transmission in neutral with the brakes not applied. Wheel chocks can be applied to a non-steered axle for safety.
- i. Re-center the steering and repeat step 4.5.1.g at higher steering-wheel speeds. If no guidance is provided in the test plan, repeat in 30 deg/sec increments, starting from 30 deg/sec, until reaching the catch-up steering-wheel torque limit or other predetermined maximum speed (e.g., 120 deg/sec). The catch-up steering-wheel torque limit is characterized by a steep increase in steering torque when the steering assist servo pump can no longer provide sufficient oil flow to the servo at higher steering-wheel rates. Perform step 4.5.1.h after each test event.

j. The test series may be repeated without power steering active or with the service brake applied. Without power steering, the maximum steering-wheel rate will likely be limited by steering robot torque capability or human strength limits.

k. Record the type of road surface (e.g., asphalt, concrete, or gravel), frictional coefficient of the test surface (if known), and the ambient road temperature.

Note: For good test repeatability, monitor the steering servo oil temperature throughout testing. If the oil temperature deviates significantly from the standard conditions at the start of testing, allow the oil to cool before continuing.

4.5.2 Vehicle Moving At Low Speed (Parking Characteristics).

a. Repeat the basic test steps described in paragraph 4.5.1, but with the vehicle moving at a predetermined vehicle speed less than 10 kilometers per hour (km/hr) (6 miles per hour (mph)). If no guidance is provided in the test plan, choose a vehicle speed based on the vehicle creep speed (engine at idle speed) in the lower gear ranges.

b. If no guidance is provided in the test plan, test at steering-wheel speeds ranging from 120 deg/sec to the catch-up steering wheel torque limit, the performance limits of the steering robot, as is practical, in 60 deg/sec increments. Vehicle speed, steering rate, and steering waveform will significantly affect torque levels and must be carefully controlled and calculated/reported in data processing.

c. Testing may be repeated at higher engine speeds, with a corresponding increase in vehicle speed. Steer amplitudes may need to be reduced to avoid tire forces due to cornering.

Note: Review the two notes in paragraph 4.5.1. Also, testing with the vehicle moving may require substantial test space, pre-planning, and trial runs to ensure sufficient test space is available. Repositioning the vehicle between test events may be necessary.

4.5.3 Vehicle Moving (based on AVTP 03-30³², Steering and Maneuverability, paragraph 4.4).

Note: This procedure was maintained in the TOP for historical purposes. However, if the intent is to evaluate low-speed steering effort consistent with parking maneuvering, the procedure described in paragraph 4.5.2 is preferred.

a. Determine the steering wheel angle necessary for the vehicle to traverse a circle having the radius specified in the test plan (this radius should normally be 30 meters).

b. Stabilize the vehicle on a straight line tangential to the required circle at the specified vehicle speed. (Unless otherwise specified in the test plan, the speed for vehicles under 10-ton gross vehicle weight (GVW) is 32 km/h, and the speed for vehicles over 10-ton GVW is 16 km/h).

- c. Turn the steering wheel as quickly as possible to the angle specified in paragraph 4.5.3.a, follow the circle for 180 degrees, and then exit along the tangential line and measure:
 - (1) The steering effort during the complete maneuver.
 - (2) The time required to steer from the neutral position to the angle specified in paragraph 4.4.2.a.
 - (3) The time required to return to the neutral position.
- d. Repeat the test twice in each direction of turning.
- e. Repeat the test for each alternative vehicle speed and circle diameter presented in the test plan.
- f. For vehicles with power steering, perform the test with and without the power steering (if possible).

4.5.4 Dead-Engine Steering.

The impact on steering effort increase and potential degradation in control due to a loss of steering power assist can be assessed with the Dead Engine Steer test (or Engine-off Steering test).

- a. Install a calibrated steering-wheel angle and torque measuring device on the steering wheel or in place of the steering wheel for testing. Record steering-wheel angle, δ_{SW} , and steering torque, M_{SW} , continuously with a digital data acquisition system for the duration of each test event below.
- b. Mark out the test course shown in Appendix A on a smooth, level, open area.
- c. To establish the test vehicle's steering effort baseline, the vehicle must first negotiate the course at various speeds with the engine on and transmission engaged.
- d. The test vehicle is then driven at 10 km/h when entering the course at "A". Shut off the engine, and disengage the transmission 10 meters before the Steer Point. Attempt to drive the vehicle through the course to exit at "C".
- e. Repeat paragraph 4.5.4.d but this time entering the course at "B".
- f. If the vehicle satisfactorily completes the above procedures, repeat paragraphs 4.5.4.b and 4.5.4.c with the entry speed progressively increased in stages, until a maximum safe speed is reached without signs of instability while remaining within the course boundaries.

g. For comparison purposes repeat the test for various combinations of engine on/ off and transmission engaged/ disengaged.

h. The maximum entry speed for point "A" and for point "B" and steering-wheel torque measurements are recorded as the results of this test.

Note: Testing may be limited by driver strength, so it is recommend to repeat testing with multiple drivers.

4.6 Turning.

The turning ability of the vehicle is a measure of maneuverability indicated by the minimum circle that the vehicle can negotiate and, when required, the minimum road widths into which the vehicle can complete a 90-degree (T-junction) turn.

4.6.1 Minimum Turning Circle Diameter.

a. To determine the minimum turning circle diameter for wheeled and tracked vehicles measure the following circumferences (see Appendix B) for the tightest turns in both steer directions on a dry, concrete or asphalt surface, operating the vehicle at minimum speed (unless otherwise specified):

(1) "Curb-to-curb" – the circumference of the circle described by the outer edge of the outside front wheel or track.

(2) "Wall-to-wall" – the circumference of the circle described by the outermost point of the vehicle when turning at maximum angle. A small wheel or a water spray device positioned at the outermost point of the vehicle is usually used. For wheeled and tracked combat vehicles, the test is conducted with the main weapon positioned horizontally, both in 12 o'clock and 6 o'clock positions.

(3) "Turning circle" – the circumference of the circle measured at the center of the tire contact of the outermost wheel (wheeled vehicle only).

Note: It may be informative to measure the inner trace diameter measurement, measured at the trailing axle tire bulge (curb to curb) or measured at the trailing outermost point on the test item (wall to wall) as well.

b. For vehicle combinations, measure turning circumferences of the prime movers both with and without the towed unit. Observe airlines, electrical wires, tow-bar, safety chains, and the towed unit itself for any interference that would limit the measured turning circle or cause equipment damage.

c. For tracked vehicles and off-road construction or agricultural vehicles, when applicable, measure the circumference traced when using each type of steering provided (e.g., hand wheel or steering brakes).

4.6.2 Minimum Road Width.

Determine the minimum road width of a T-junction (see Appendix C, Figure C-1) that a vehicle or vehicle combination can successfully negotiate using either of the following methods.

a. Calculation Method.

(1) The appropriate inner and outer circle diameters, for right-hand lock, are obtained from the procedure in paragraph 4.6.1. These may be the wall-to-wall diameters, or the curb-to-curb diameters, as appropriate.

(2) The minimum road width for a maximum right-hand turn is calculated as shown in Appendix C, Figure C-2.

(3) A similar calculation is performed for the left steer direction.

(4) The result that is reported is the larger of the calculation for either the right-hand turn or the left-hand turn. If required, the result can be confirmed by setting up a simple T-junction on the course, of the larger dimension calculated above, and attempting to negotiate it without interference.

b. Practical Method (see Appendix C, Figure C-3).

(1) Mark out a right-angled datum corner (ABC) on the ground.

(2) With the vehicle positioned at A and facing parallel to the line AB, the vehicle is driven forward slowly ($V \leq 5$ km/h) until facing parallel to line BC, at position C.

(3) The accuracy of the result depends on a close agreement between measurements X and Y; therefore, repeat paragraph 4.3.2.b(2) until X and Y approximate each other.

(4) Whichever of measurements X and Y is the larger is presented as the minimum road width for a right-hand turn.

(5) Repeat the procedure for a left-hand turn.

(6) The overall result of the test is the greater of the measurements for either the right-hand turn or the left-hand turn. However, both turn direction results should be reported.

Note: The minimum road width measurement is dependent on a number of factors including vehicle unit wheelbase, track, steering characteristics, hitch distances, and off tracking (see paragraph 4.7).

4.7 Off Tracking.

Off tracking is a measure of maneuverability indicated by the difference in turn radii from the turn center to the vehicle centerline at the foremost and rearmost axles of a vehicle or vehicle combination. The rearmost axle generally tracks a smaller radius than the foremost axle. The amount of off tracking varies with the wheelbase of a vehicle unit (or combination) and the radius of the turn, and increases along the path length of the turn, up to a maximum value at 270 degrees of turning¹¹.

4.7.1 Maximum Off Tracking.

Determine the maximum off tracking characteristics of a vehicle or vehicle combination in accordance with SAE International J695.

4.7.2 Swept Path.

- a. Set up the test course shown in Appendix D, Figure D1, based on the pre-determined turning radius, vehicle reference point, and angle between entry and exit established in the test plan.
- b. Enter the course at a speed of less than 5 km/hr. Unless otherwise stated in the test plan, the test should be performed for path angles of 90 degrees, 180 degrees, and 270 degrees.
- c. Throughout the tests, mark on the ground the trajectories of the innermost and outermost points of the vehicle.
- d. From the center of the turn, trace radial lines at angles of every 10 degrees. For each of these angles, measure the distance from the turn center point to the intersection of both the innermost and outermost trajectories (traced in paragraph 4.13.b) with the appropriate radial line.
- e. Repeat the test for all the circle diameters and angles of turn presented in the test plan for each direction of turn.
- f. Example plots of swept paths are shown in Appendix D, Figure D-2.

4.8 Slalom.

Slalom tests are used to assess maneuverability at increasing speeds and steer rates. Slalom tests may also be useful for evaluating the lane changing ability of vehicles at different speeds, accident avoidance assessments (including vehicle responsiveness, stability and controllability), driver training, handling assessments, and steering system characteristics of tracked vehicles. Slalom tests are considered closed-loop maneuvers.

4.8.1 Constant Step Slalom.

- a. For wheeled vehicles, install outriggers if yaw and roll instability regions of vehicle performance will be approached or exceeded.
- b. Set up the course shown in Appendix E, Figure E-1, with the initial distance (d) set to 10 meters. Traffic cones are used to mark the slalom course.
- c. Cross the line (1-1a) at the lowest vehicle speed specified in the test plan and drive a straight line through the section (1-2); attempt to continue through the remainder of the course (2-5) whilst keeping the speed as steady as possible (at this same speed). The time needed to cross the section (3-4) is to be measured.
- d. Repeat these steps at the various speed increments specified in the test plan until one of the following occurs:
 - (1) The maximum speed specified in the test plan is reached.
 - (2) It becomes impossible to cross the test area without knocking the cones down.
 - (3) A speed is reached where yaw or roll instability is approached or occurs.

Note: Roll instability occurs when the vehicle rollover threshold is exceeded and roll motion becomes unbounded (possibly accelerating). For this TOP, roll instability is indicated when all tires on the inner track of a cornering vehicle lift from the ground plane. The transition from a single tire lift to all inner track tires lifting may occur quickly. Depending on the purpose of the test, the test maneuver, and the attributes of the vehicle, it may not be prudent or necessary to test until full roll instability is observed. In all cases, caution should be exercised. Outriggers may need to be adjusted to prevent imminent rollover while still allowing the point of roll instability to be identified (if necessary).

- e. Repeat the entire procedure (paragraphs b through d) with the distance (d) set in turn to 15, 20 and 30 meters.
- f. Repeat the entire procedure (paragraphs b through e) with a different driver.

Note: The general procedure may be modified and adapted as necessary to meet specific test plan guidance.

4.8.2 Increasing And Decreasing Step Slalom.

Increasing and decreasing step slalom tests are less common and are not described in this TOP for brevity. Refer to AVTP 03-30 (paragraph 4.7.2) for guidance. Ensure that outriggers are installed on wheeled vehicles when appropriate.

4.9 Entry Control Point (ECP) Maneuverability (see Appendix F).

ECP Maneuverability testing is a low-speed maneuverability test designed to determine a vehicle's capability to negotiate a simulated ECP course, per Army TM 5-853-2. The course, shown in Appendix F, is composed of a series of standard hollow plastic Jersey barrier traffic obstacles, positioned on two 12-foot wide lanes, spaced to slow vehicles on their approach to a specific target.

- a. Set the barriers to the minimal gate distance specified in the test plan. If no other guidance is provided, it is recommended that the initial minimum gate spacing (in feet) be set to twice the desired drive through speed (in mph).
- b. Initiate the test at the minimum vehicle speed specified in the test plan, or at a minimum safe speed determined by the test engineer.
- c. Maintain the speed while applying the smoothest steering input necessary to negotiate the course.
- d. Adjust the minimal gate distance and/or vehicle speed until optimum vehicle maneuverability is developed or the target vehicle speed has been achieved.
- e. The last (fifth) traffic obstacle gate is optional and dependent on the actual ECP specified for testing.

4.10 Pivot Steering.

The Pivot Steering maneuverability test determines the shortest time necessary for a tracked vehicle (or a wheeled vehicle with skid steer capability) to make a 360-degree pivot turn. The engine is brought to nominal rpm and the steering is turned to the maximum left or right position. Tests are conducted on a level concrete surface. The time required to turn 360 degrees from a stop and the diameter of the turning circle traced by the gun tube and/or hull during the turn are measured. The test is repeated as necessary, in both directions, to achieve statistically significant results.

4.11 Drift.

Drift is the tendency of a vehicle to deviate slightly from a straight-ahead path when the vehicle steering wheel is allowed to assume its own self-centering position. Drift, as measured in this test, is that which is caused by the vehicle itself (e.g., from wheel alignment, asymmetrical loading, or tire behavior/condition), as opposed to vehicle drift induced by the crown of the road, banked curves, or other outside influences. While some test runs should be conducted with the test vehicle in its "as received" condition (asymmetric loading, underinflated tire, etc.), at least one test run shall be made with a balanced load, properly inflated tires, and correct wheel alignment.

- a. While operating the vehicle on a straight, level road at its minimum sustained speed, without brake application, release the steering wheel and record the amount of drift from a straight path per 30 meters of travel or by a similar measurement reference.
- b. To negate the potential effects imposed by the roadway, the test should be performed in both test course directions, along the same path, with the results averaged.

Notes:

1. Cross wind will affect the drift of a vehicle, so it is recommended to conduct the testing with the wind speed conditions as low as possible (even lower than the minimum requirement specified in paragraph 3.3). Averaging the road direction results will minimize cross wind effects, but wind speed and direction is not always consistent over time.
2. This procedure may also be adapted to assess steering pull where the average steering torque required to maintain a straight path is determined.

4.12 Self-Steer During Braking.

Steering characteristics of a vehicle may be sensitive to suspension ride steer (see SAE International J670, paragraph 5.7.1.13) and insufficient caster and spindle trail (see SAE International J670, paragraphs 5.5.2.3 and 5.5.2.4), particularly during hard braking. Steering kinematics on a steerable axle may be asymmetric in some cases and result in the vehicle tending to steer out of its lane when braking (due to ride steer). Furthermore, vehicles with insufficient caster/spindle trail to compensate for pitch angle changes experienced during hard braking may experience a condition where the pneumatic trail (see SAE International Surface Vehicle Information Report J2047³³, Tire Performance Terminology, paragraph 10.7.1) shifts forward of the wheel's steering axis, self-steering the vehicle to the right or left.

- a. Install a calibrated steering-wheel angle and torque measuring device on the steering wheel or in place of the steering wheel for testing. Record steering-wheel angle, δ_{sw} , and steering torque, M_{sw} , continuously with a digital data acquisition system for the duration of each test event below.
- b. On a straight, level roadway, mark a test lane 3.6 m (12.0 feet) wide.
- c. Drive straight into the lane at 32 km/hr (20 mph) and initiate a full-effort braking event with a pedal force within the 445 to 667 Newtons (100 to 150 pound-force) range.
- d. When issues with ride steer are being investigated, the driver shall hold the steering wheel straight ahead when braking, unless steering action is required to avoid vehicle instability.
- e. When issues with trail are being investigated, at the discretion of the test engineer, the driver shall either allow the steering wheel to self-steer while steering wheel angle is measured or hold the steering wheel straight ahead while steering torque is measured.

f. Measure and record lateral displacement from the initial path of the vehicle during the braking event. Note any unsafe conditions experienced.

g. Repeat the test event a sufficient number of trials to produce statistically significant results.

h. Testing may be repeated with the driver providing corrective steer measures to stay straight in the lane, while measuring and recording steering torque.

i. The cause of the self-steering characteristic should be investigated and reported with the test results if identified.

Note: Sufficient space on the test course is required to avoid unsafe conditions. Outriggers are recommended when testing vehicles with excessive self-steering characteristics. Drivers may abort a test run with corrective steering to avoid unsafe conditions or vehicle instability.

4.13 On-Center Handling.

On-center handling tests provide an objective description of the steering feel and steering precision (including backlash) of a wheeled vehicle during nominally straight-line driving and in negotiating large-radius bends at high speeds but low lateral accelerations. On-center handling is concerned primarily with features that directly influence the driver's steering input (and feel). Two open-loop steering maneuvers are used- the Weave Test and the Transition Test. The Weave Test examines the outer edge of the steering response hysteresis loop, while the Transition Test examines the transition from straight line running to the edge of the steering hysteresis loop. Driver inputs and vehicle responses are measured and recorded, and characteristic values are calculated.

4.13.1 Weave Test.

Conduct the weave test in accordance with TOP 02-2-600.

4.13.2 Transition Test.

Conduct the transition test in accordance with TOP 02-2-600.

Note: To gain further insight into On-Center steering testing, in addition to TOP 02-2-600, review the following:

1. ISO 11012, Heavy commercial vehicles and buses- Open-loop test methods for the quantification of on-centre handling- Weave and transition test.

2. ISO 13674-1, Road vehicles-Test method for the quantification of on-centre handling- Part 1 Weave test.

3. ISO 13674-2, Road vehicles-Test method for the quantification of on-centre handling- Part 2 Transition test.

4.14 Handling.

Handling tests, aside from the objective on-center steering tests described in paragraph 4.13, generally consist of subjective assessments of specific vehicle handling properties during closed-loop maneuvers on proving ground courses. Subjective assessments can be quantified using rating scales. It is recommended that the rating scale presented in SAE International J1441, be used to quantify subjective handling assessments by test drivers and engineers. The SAE rating scale is unipolar and continuous with ten rating points (from 1 to 10). Fractional ratings are allowed. Every other rating point is assigned an adjective ranging from very poor to excellent. Specific evaluation criteria (e.g., steering sensitivity, response lag) and a framework (e.g., military tactical vehicle or sports car) must be determined before testing starts with specific test maneuvers. Use of reference vehicles is recommended for comparison purposes. Use of a jury consisting of a small group of expert evaluators is also recommended, but non-expert evaluators may be used when appropriate. Additional guidance on use of the scale is provided in SAE International J1441.

4.15 Overall Steering Performance.

a. Typically, all military vehicles must conduct endurance testing over various standard test courses for a prescribed distance or number of operating hours to provide data for evaluating its reliability, maintainability, human factors, and safety suitability. During the endurance test, observe and assess the overall steering performance including the steering effort required by the driver, the responsiveness of the vehicle (driver control) under each condition of deployment (e.g., terrain, load, temperature, vehicle and engine speeds), and fatigue. The rating system described in paragraph 4.14, Handling, may be used for overall assessment of steering system performance.

b. When steering effort appears to be excessive (test driver observation), vehicle control is questionable, or a particular capability of the steering system requires investigation, conduct a more detailed assessment of steering performance on the 1-mile steering performance course (see Appendix G) with the vehicle instrumented to measure driver effort at the steering wheel, steering wheel position, and fluid temperature and pressure in the hydraulic steering mechanism (when applicable). Constantly record and identify the measurements according to maneuver or event (i.e., figure-eight turns, percent slope, etc.) as the vehicle negotiates the course in both directions at various speeds up to its maximum safe speed.

4.16 Steady-State Circular (Skidpad) Test.

This test is used to determine the steady-state directional control response (and stability) of a wheeled vehicle unit or vehicle combination. The primary goal is to establish the relationship between steering wheel angle and lateral acceleration⁹. Key response graphics and properties obtained from the test may include the handling diagram, understeer/oversteer gradient, roll gradient, direction response limits, characteristic speed (during understeer), critical speed (during oversteer), and steering wheel angle, steering wheel torque, roll, and sideslip characteristic curves.

- a. The steady-state circular test is typically conducted in accordance with SAE International J2181. This procedure is considered a constant radius method. See the notes at the end of this section for alternative methods.
- b. Install outriggers on the test vehicle when appropriate to prevent rollover.
- c. Prior to executing the circular steer test, drive the vehicle in a straight line at low speed and record zero levels for the test instrumentation.
- d. Operate the test vehicle at a constant vehicle speed around a circular test course having a nominal diameter of 61 meters (based on the test plan, circles with larger diameters may be designated).
- e. Conduct the test in both left and right steer directions at constant vehicle speeds ranging from 8 km/hr up to maximum attainable speed, limited by either the available vehicle power or vehicle instability in the roll or yaw axis.
- f. Drive the vehicle for at least one lap at each speed to allow the required data to be recorded.

Notes:

1. An alternative method for heavy vehicles, known as the constant speed, variable steer angle test, is described in ISO 14792. Alternative methods for passenger cars and light trucks are described in SAE International J266, and ISO 4138. Methods where the turn radius is not constant include effects from Ackerman gradient.
2. Understeer is a highly desirable characteristic of wheeled vehicles at highway speeds, whether driving straight ahead or in a turn. Understeer:
 - (a) Provides directional stability.
 - (b) Results in a natural response to steering input.
 - (c) Controls the vehicle's sensitivity to steering input.
 - (d) Reduces the time required for the vehicle to respond to steering input (see the U.S. Army Combat Capability Development Center (CCDC) Ground Vehicle Systems Center (USACDCGVSC) Army Mobility Handbook³⁴).
3. Steering sensitivity (lateral acceleration gain) and yaw velocity gain both increase with vehicle speed, potentially to the point of creating dangerous conditions at high speed if insufficient understeer is designed into the steering characteristics. Understeer essentially controls steering sensitivity at higher speeds.

4.17 Response Gain (Including Steering Sensitivity).

Lateral acceleration gain (steering sensitivity) and yaw velocity gain are measured in the linear range of steering (0.1 to 0.3 *g* for most military wheeled vehicles) and are vehicle speed dependent. The linear range is determined during the Steady-State Circular Test, paragraph 4.16.

- a. Response gain tests are conducted in accordance with SAE International J266, paragraph 7.6.
- b. Because of the wide range of wheeled vehicles and vehicle combinations tested and potential test area space limitations, modifications to the prescribed steer maneuver may be required, provided the general intent is observed. If a steering robot is utilized to execute the steering inputs (preferred method), a step steer or ramp steer function is used (see Appendix H). The ramp steer maneuver will reduce steering and response overshoot before levels of steady state are achieved. When choosing a ramp rate, the goal is to ramp as quickly as possible while trimming the overshoot to a reasonable level. If overshoot is not an issue, only use the step steer function. Additional (informative) guidance on selection of the ramp time is given in ISO 7401, clause 10.
- c. For vehicles with low rollover thresholds, the goal is to test with as high a lateral acceleration level (in the linear range) as possible, while not risking a rollover event. Use of low lateral acceleration levels may result in noisy or inconsistent data results.
- d. Since lateral acceleration levels are generally low, use of outriggers is potentially unnecessary. The need for outriggers should be considered on an individual basis.
- e. Testing is performed on a flat, preferably level, paved road surface. If the test surface has a slight slope, tests should be performed in both course directions, so that results can be averaged. Driving over crowns in test surfaces shall be prohibited.
- f. Prior to executing the response gain tests, drive the vehicle in a straight line, on a level roadway, at low speed (not to exceed 16 km/hr (10 mph)) and record zero levels for the test instrumentation.

4.18 Transient Response.

Steering sensitivity and yaw velocity gain (see paragraph 4.17) may also be measured using frequency response test methods.

- a. Frequency domain response tests are conducted in accordance with ISO 7401, clauses 12 and 13. The linear range for most military wheeled vehicles is between 0.1 and 0.3 *g*.
- b. For vehicles with low rollover thresholds, the goal is to test with as high a lateral acceleration level (in the linear range) as possible, while not risking a rollover event. Use of low lateral acceleration levels may result in noisy or inconsistent data results.

c. Testing is performed on a flat, preferably level, paved road surface. If the test surface has a slight slope to it, tests should be performed in both course directions, so that results can be averaged. Driving over crowns in test surfaces shall be prohibited.

d. Prior to executing the frequency response tests, drive the vehicle in a straight line, on level roadway, at low speed and record zero levels for the test instrumentation.

e. The frequency response tests described here are to be conducted without outriggers, since the added inertia of the outriggers will affect the dynamics of the test vehicle. Consequently, care should be taken to stay at lateral acceleration levels that will not exceed the rollover threshold of the test vehicle.

f. When testing vehicle combinations, care should be taken to ensure the steering amplitudes chosen do not cause extreme accelerations of the trailer due to rearward amplification

g. Tests are conducted at multiple speeds to characterize the speed dependency of steering sensitivity and yaw velocity gain.

Note: From the frequency response plots, the gains at the lowest frequency where good coherence exists are reported as the lateral acceleration gain (steering sensitivity) and yaw velocity gain.

4.19 Emergency Lane Change.

Because vehicle behavior during emergency evasive maneuvers is highly dependent on the characteristics of the maneuver performed, either or both of the lane change courses shown in Appendix I may be used to define vehicle performance in this area. Both tests assess controllability and stability (if limit ranges are achieved).

- a. Cross the course entrance at the lowest vehicle speed specified in the test plan.
- b. Maintain the speed while applying the smoothest steering necessary to negotiate the course.
- c. Repeat the test at small increasing speed increments until:
 - (1) The maximum vehicle/specified speed is reached (per the test plan).
 - (2) The roll stability limit of the vehicle is reached (see the description of roll instability in paragraph 4.8.1).
 - (3) It becomes impossible to negotiate the test course without knocking cones down.
- d. Record parameters and note the vehicle behavior during the test.

- e. Repeat the test with in the opposite course direction and with multiple test drivers, if practical.
- f. Typically the test is conducted on a level, paved course. If stipulated in the test plan, a gravel course can be substituted.
- g. To prevent rollover at the higher test speeds, fitting the vehicle with an outrigger system should be considered.

4.20 Electronic Stability Control.

Electronic stability control system tests are conducted in accordance with TOP 02-2-718A. Slowly Increasing Steer (SIS), Sine with Dwell, and J-Turn tests are used to assess the effectiveness of yaw and roll stability systems. Test vehicles are equipped with outriggers to avoid rollover.

4.21 Lateral Stability Of Vehicle Combinations.

- a. The lateral stability of vehicle combinations is characterized by:
 - (1) Rearward amplification of lateral acceleration and yaw velocity.
 - (2) Dynamic off tracking.
 - (3) Zero-damping speed.
 - (4) Yaw damping.
- b. Lateral stability of vehicle combination tests are conducted in accordance with ISO 14791.

4.22 Control On Adverse Terrain.

a. The effects of various terrain conditions on steering control are assessed by operating the vehicle in terrain environments that typify projected vehicle use; e.g., mud, sand, ice, snow. For these tests, use traction-assist devices when appropriate and specified. An all-wheel-drive vehicle may encounter difficulty in steering in mud or snow. To test steering effectiveness in mud or snow oscillate the steering alternately between extremes of left and right steer. Recovery or mobility by this method will be particularly evident in an articulated vehicle and certain other vehicles depending upon transmission design. Observe effects on tracks and suspensions, especially with respect to sprocket slipping, track throwing, and excessive accumulation of soil and debris.

b. Assess wheeled vehicle steering systems on the wave (frame twister), radial washboard, and spaced bump courses (TOP 01-1-011B) in addition to the weather-induced adverse terrains above. Observe for any interference, bindings, weaknesses, or other unsatisfactory features of the system.

c. Check conformance of standard systems with specifications as well as qualitatively. Conduct more detailed testing on newly developed systems, including comparison with existing systems. When steering efforts are measured in environments more severe than those of accepted standards, quantitative measurements are required, using instrumentation appropriate for the condition.

4.23 Control On Side Slopes.

Vehicle steering control on side slopes is assessed during the conduct of the side slope tests described in TOP 02-2-610. The 20-, 30-, or 40-percent hard-surfaced side slopes are used depending upon the vehicle design and specifications. Operate the test vehicle, at both curb and gross vehicle weight conditions, the length of the specified side slope in both directions. Observe and record the maximum safe vehicle maneuverability (e.g., traversing in a sine wave pattern from one extreme to another on the side slope), tire roll characteristics, and any loss/degradation of steering control.

Note: For vehicles equipped with ESC systems, report any circumstances of ESC activation on side slopes. It may be necessary to disable the ESC system before proceeding with tests on side slopes.

5. DATA REQUIRED.

a. General Vehicle and Test Characterization.

- (1) Vehicle identification: manufacturer, type, registration number, serial number.
- (2) Odometer mileage.
- (3) Vehicle payload distribution (amount of payload and location).
- (4) Wheelbase and track.
- (5) Vehicle weight distribution.
- (6) Vehicle center of gravity location (longitudinal, lateral, and vertical).
- (7) Tire selection, tire pressures, central tire inflation system setting, tire condition, and tread depth (TOP 02-2-704A).

heights.

- (8) Suspension configuration (highway, off-road, etc.) and suspension or vehicle trim

- (9) Drivetrain configuration (2x4, 4x4, driveline locks, etc.).

- (10) Vehicle wheel alignment data (if available).

- (11) Suspension and steering system condition.

- (12) Test course identification, dimensions, and description of operating conditions.

- (13) Ambient weather conditions (including temperature and wind speed).

- (14) Test instrumentation description.

b. Geometric Stability Ratio.

- (1) Average vehicle track.

- (2) Center of gravity height, above that ground.

- (3) Geometric stability ratio.

c. Static Rollover Threshold (Tilt-table).

- (1) Platform tilt angle, ϕ , at liftoff of each wheel.

- (2) Simulated lateral acceleration threshold, a_y , at liftoff of each wheel.

- (3) Instances of fluid leakage (along with tilt angle if observed).

d. Cramping Angle and Steering Ratio.

- (1) Left and right cramping angle and associated steering-wheel angles from the straight-ahead position.

- (2) Number of turns of steering wheel, maximum left to maximum right.

- (3) Steering-wheel (hand wheel) angle.

- (4) Left and right wheel angle.

- (5) Passive (purely kinematic) or active steering.

- (6) Tilt-steering position (if applicable).

- (7) Suspension setting and vehicle/suspension trim heights.
- e. Steering Effort.
 - (1) Test maneuver conducted.
 - (2) Test conditions (engine running, engine off, power steering on/off, parked, etc.).
 - (3) Steer direction(s).
 - (4) Steering wheel angle.
 - (5) Steering-wheel speed.
 - (6) Steering torque (effort).
 - (7) Vehicle speed.
 - (8) Engine speed.
 - (9) Turning radius (for paragraph 4.5.3).
 - (10) Capability of steering system to maintain directional control (for paragraph 4.5.4).
- f. Turning.
 - (1) Minimum turning circle diameters, left and right directions.
 - (2) Vehicle(s) interferences limiting measurement.
 - (3) Minimum road widths for 90-degree turns, left and right directions.
- g. Off Tracking.
 - (1) Reference turning radii and associated vehicle reference point (e.g., center of the front axle).
 - (2) Turning radii of the vehicle (or vehicle combination) front axle center point and rear axle center point along the vehicle path when negotiating the turn.
 - (3) Turning radii of the contact center of the outermost and innermost tires of the vehicle (vehicle combination) along the vehicle path when negotiating the turn.
 - (4) Turning radii of the outermost and innermost points of the vehicle (vehicle combination) along the vehicle path when negotiating the turn.

- (5) Angle between entry and exit.
- (6) Direction of turn.
- (7) Vehicle speed.
- h. Slalom.
 - (1) Configuration of slalom course.
 - (2) Traffic cone spacing, d, for each test event.
 - (3) Vehicle speed and maximum speed.
 - (4) Yaw velocity (each vehicle unit).
 - (5) Lateral acceleration (each vehicle unit).
 - (6) Roll angle (each vehicle unit).
 - (7) Sideslip angle (each vehicle unit).
 - (8) Course direction.
 - (9) Time to cross essential sections of the test course.
 - (10) Observations of wheel lift, spinout, or outrigger contact if occurred and time of occurrence.
- i. ECP Maneuverability.
 - (1) Configuration of ECP course.
 - (2) Minimal gate distance.
 - (3) Speed through course.
 - (4) Vehicle behavior (driver feedback and video coverage).
 - (5) Factors limiting performance (turn ability, vehicle speed, vehicle protrusions).
- j. Pivot Steering.
 - (1) Gear range.
 - (2) Engine speed at start of turn.

- (3) Time to complete 360-degree turn.
 - (4) Angular velocity.
 - (5) Turning diameter(s).
- k. Drift.
- (1) Vehicle load distribution.
 - (2) Tire pressures.
 - (3) Amount of drift versus distance traveled, reported separately for each direction of travel along with the average value.
 - (4) Test course and location on course.
 - (5) Road side slope, if known.
 - (6) Cross wind magnitude.
- l. Self-Steer During Braking.
- (1) Vehicle load distribution.
 - (2) Tire pressures.
 - (3) Vehicle speed.
 - (4) Brake pedal force.
 - (5) Steering wheel angle.
 - (6) Steering torque, before and during the braking event (to report the difference).
 - (7) Yaw velocity.
 - (8) Lateral displacement from initial path.
 - (9) Cause of self-steer (if identified).
- m. On-Center Handling. Refer to TOP 02-2-600.

n. Handling. In addition to the objective data required for the test or maneuver during which handling is to be evaluated, subjective rating scale worksheets (consistent with SAE International J1441) shall be completed by the drivers/test engineers operating the vehicle. Each work sheet shall indicate:

- (1) Evaluation criteria (e.g. steering sensitivity, response lag).
- (2) Framework (e.g., military tactical vehicle or sports car).

o. Overall Steering Performance.

(1) Observations and evaluations of steering performance during endurance operations on various terrains, including driver fatigue and convenience and safety of control locations.

- (2) For each maneuver or event performed on the steering performance course:
 - (a) Maximum steering wheel torque.
 - (b) Maximum steering wheel angle.
 - (c) Vehicle speed range.
 - (d) Maximum fluid temperature and pressure (mostly applicable to tracked vehicles).

p. Steady-State Circular Test.

- (1) Nominal diameter of turning circle.
- (2) Longitudinal and lateral velocities (generally single or first vehicle unit)
- (3) Yaw velocity (each vehicle unit).
- (4) Lateral acceleration (each vehicle unit).
- (5) Steering wheel angle.
- (6) Sideslip angle (generally single or first vehicle unit).
- (7) Roll angle (each vehicle unit).
- (8) Sensor locations.
- (9) Steering ratio in effect for test course turn radius.

(10) Observations of wheel lift, spinout, or outrigger contact if occurred and details of occurrence.

(11) Factors limiting performance (instability, engine power, etc.).

(12) Ackermann steer angle if constant radius test methods are used.

q. Response Gain.

(1) Test maneuver description.

(2) Longitudinal and lateral velocities (generally single or first vehicle unit).

(3) Yaw velocity (each vehicle unit).

(4) Lateral acceleration (each vehicle unit).

(5) Steering wheel angle.

(6) Sideslip angle (generally single or first vehicle unit).

(7) Roll angle (each vehicle unit).

(8) Sensor locations.

r. Transient Response.

(1) Test maneuver description.

(2) Longitudinal and lateral velocities (generally single or first vehicle unit).

(3) Yaw velocity (each vehicle unit).

(4) Lateral acceleration (each vehicle unit).

(5) Steering wheel angle.

(6) Sideslip angle (generally single or first vehicle unit).

(7) Roll angle (each vehicle unit).

(8) Sensor locations.

s. Emergency Lane Change.

(1) Description of test course (track dimensions) and course direction.

- (2) Maximum speed through course.
 - (3) Vehicle behavior (driver feedback and video coverage).
 - (4) Longitudinal and lateral velocities (generally single or first vehicle unit).
 - (5) Yaw velocity.
 - (6) Lateral acceleration.
 - (7) Sideslip angle (generally single or first vehicle unit).
 - (8) Roll angle.
 - (9) Sensor locations.
 - (10) Factors limiting performance (roll stability, yaw response, vehicle speed, etc.).
 - (11) Observations of wheel lift, spinout, or outrigger contact if occurred and time of occurrence.
- t. Electronic Stability Control. Refer to TOP 02-2-718A.
 - u. Lateral Stability of Vehicle Combinations.
 - (1) Longitudinal and lateral velocities (generally single or first vehicle unit).
 - (2) Yaw velocity (each vehicle unit).
 - (3) Lateral acceleration at center of gravity (each vehicle unit) and lateral acceleration of the first vehicle unit at the centerline of the first axle.
 - (4) Steering wheel angle.
 - (5) Articulation angles or articulation angular velocity between the vehicle units.
 - (6) Off tracking of the most severely off tracking axle of the vehicle combination.
 - (7) Roll angle (each vehicle unit).
 - (8) Sensor locations.
 - (9) Observations of wheel lift, spinout, or outrigger contact if occurred and time of occurrence.

v. Control on Adverse Terrain. Observations and evaluations relative to response and control of steering system for each terrain condition.

w. Control on Side Slopes.

(1) Grade of slope.

(2) Vehicle speed.

(3) Payload distribution.

(4) Tire inflation pressures and roll characteristics during maneuver.

(5) Observation of degree of control maintained during each test condition.

(6) Vehicle driveline settings.

(7) ESC state- on or off.

6. PRESENTATION OF DATA.

a. General Vehicle and Test Characterization. Narrative, tabular, graphical, pictorial, or other format presentation as appropriate.

b. Geometric Stability Ratio. Narrative of Geometric Stability Ratio or Static Stability Factor, as appropriate. Report the average vehicle track and center of gravity height used.

c. Static Rollover Threshold. Tabular presentation of simulated lateral acceleration and side slope angle versus wheel liftoff location for each vehicle direction and configuration. Photographs of vehicle at the rollover threshold. Narrative of fluid leaks or other abnormalities and corresponding tilt angle of occurrence.

d. Cramping Angle and Steering Ratio.

(1) Cramping Angle. Narrative and/or tabular presentation of cramping angle in both directions of steer and corresponding steering wheel angles.

(2) Steering Ratio.

(a) Narrative describing whether the steering system is passive (purely kinematic), active, and single axle or multi-axle, with as much description of the steering system and corresponding axle's suspension as relevant and known.

(b) Graphical presentation of left wheel angle, right wheel angle, and mean reference steer angle (each on the ordinate) versus steering wheel angle (abscissa), using averaged data from multiple trials in each steer direction. See Appendix J, Figure J-1 for an example plot.

(3) Graphical presentation of steering ratio (ordinate) or overall steering ratio (ordinate) versus steering wheel angle (abscissa). See Appendix J, Figure J-2 for an example plot. Appendix K provides details for the steering ratio data curve fit shown in Figure J-2 and the calculation of associated steering ratio metrics.

Notes:

1. Ackermann error as described in paragraph 5.7.3.6 of SAE International J670 may also be determined.

2. The steering ratio can be used to estimate turning diameter (see paragraph 4.6).

e. Steering Effort.

(1) Vehicle Stationary.

(a) Narrative and tabular presentation describing the test conditions, steering-wheel ranges, and steering-wheel speeds used. Graphical presentation of steering torque, M_{SW} , (ordinate) versus steering-wheel angle, δ_{SW} , (abscissa) for each test trial, as shown in Figure L-1.

(b) Report the following characteristic values (see Figures L-1 and L2), noting the associated steering-wheel angle test range and steering-wheel speeds:

a *Maximum steering-wheel torque*, left and right steer directions. It may be necessary to report average values if variation near the observed maximum value exists.

b *Steering wheel work when steering out*, left and right steer directions.

c *Steering wheel torque when steering in*, at the zero steering-wheel angle points, left and right steering directions.

d *Steering wheel work when steering in*, left and right steering directions.

e *Remaining steering-wheel angle*, left and right steering directions. This is a measure of return ability indicated by the steering-wheel angle where the restoring torque acting on the steering wheel crosses zero (torque) when steering in.

f *Steering-wheel torque variation*, left and right steering directions.

g *Catch-up steering wheel speed* and *Catch-up steering-wheel torque*, left and right steering directions. These are obtained by plotting the maximum steering-wheel torque

(ordinate), for each steering-wheel speed, versus steering-wheel angle speed (abscissa), as shown in Figure L-3. The catch-up steering-wheel speed and torque values are determined at the first measured steering wheel speed where steering torque increases suddenly. The deviation occurs when the steering assist servo pump can no longer provide sufficient oil flow to the servo at higher steering-wheel rates.

Note: If steering-wheel torque limits were reached due to excessive axle loads, potentially preventing the catch-up speed from being reached, note this with the results.

(2) Vehicle Moving At Low Speed (Parking Characteristics). Use the guidance provided in paragraph 6.e(1) for data presentation, noting additionally the vehicle test speeds.

(3) Vehicle Moving. Based on AVTP 03-30, Steering and Maneuverability, paragraph 4.4.

(4) Dead Engine Steering. Narrative presenting vehicle speed, direction of steer, maximum steering wheel effort, and capability to maintain directional control. Graphical plot(s) of steering torque (ordinate) versus time (abscissa) may be useful to demonstrate the effects of test variables (e.g., vehicle speed, steering rate and power steering condition).

f. Turning. Table showing turning circle diameters and minimum road widths for each turn direction and narrative or figures showing areas of interference.

g. Off Tracking. Narrative and tabular presentation describing the maximum off tracking characteristics, diameter and angle of reference turn, and plots of swept path results as described in Appendix D, Figure D-2.

h. Slalom. Narrative and tabular presentation describing the test maneuver, cone spacing, vehicle speed, and time to traverse the course. If relevant, include maximum yaw velocity, lateral acceleration, sideslip, and roll angle. Discuss conditions limiting vehicle speeds, such as yaw instability, roll instability, visibility, and vehicle dimensions. Lateral acceleration data shall be zeroed, filtered, and corrected for sensor placement and vehicle roll angle, as described in TOP 02-2-718A. Yaw velocity measurements referenced to the vehicle coordinate axes shall also be zeroed, filtered, and resolved into the earth-plane coordinate axes.

i. ECP Maneuverability. Narrative presenting minimal gate distances of the ECP course verses the corresponding drive through speeds. Limiting performance factors and driver comments concerning vehicle behavior will also be presented, if significant.

j. Pivot Steering. Table depicting engine speed, angular velocity, turning diameter, and time to complete a full turn for each type and direction of steer.

k. Drift. Narrative identifying vehicle tire pressures and load distribution with the resultant drift for the distance traveled.

- l. Self-Steer During Braking. Narrative and/or tabular presentation identifying the vehicle and test conditions, along with the objective measures listed in paragraph 5.1.
- m. On-Center Handling. Refer to TOP 02-2-600.
- n. Handling. Narrative and/or tabular presentation describing the evaluation criteria, framework for comparison (see paragraph 5.n), and results of subjective rating scale worksheets.
- o. Overall Steering Performance. Narrative describing the observations and evaluations of steering performance and a tabulation listing the various measured parameters for each maneuver on the steering course.
- p. Steady State Circular Test.
 - (1) Lateral acceleration data shall be zeroed, filtered, and corrected for sensor placement and vehicle roll angle, as described in TOP 02-2-718A. Yaw velocity measurements referenced to the vehicle coordinate axes shall also be zeroed, filtered, and resolved into the earth-plane coordinate axes. In steady-state turning the measured yaw velocity is equal to the earth-plane yaw velocity multiplied by the cosine of the vehicle roll angle⁸.
 - (2) Present graphs of steering wheel angle, steering wheel torque, roll angle, and sideslip (each on the ordinate) versus lateral acceleration (abscissa), showing both turn directions. Example plots are shown in SAE International J2181, Appendix C.
 - (3) If an alternative test method is used (see paragraph 4.16, Note 1), other than the constant radius method described in SAE International J2181, present a graph of path radius (ordinate) versus lateral acceleration.
 - (4) For articulating vehicles, graphs of articulation angle (ordinate) versus lateral acceleration (abscissa) and articulation angle (ordinate) versus steering wheel angle (abscissa) may be presented.
 - (5) For steady-state cornering, the product of yaw velocity and longitudinal velocity may be used for lateral acceleration. This substitution is often made because the measured yaw velocity data signal to noise ratio is generally better than with measurements from accelerometers.
 - (6) In lieu of a direct measurement of path radius (perhaps with a differential Global Positioning System), path radius can be calculated. For steady-state conditions and small side slip angles, path radius equals vehicle speed (m/s) divided by yaw rate (rad/s).
 - (7) For the constant radius test method, present the handling diagram described in SAE International J2181 (Figure C-5), for both turn directions, showing lateral acceleration (ordinate) versus the sum of the Ackermann steer minus the mean reference steer angle (degrees or radians- degrees is preferred). The mean reference steer angle for each lateral acceleration

state graphed shall be determined directly from the graph (or curve fit) of steering ratio versus mean reference steer angle (see paragraph 6.2.4.c) for each steering wheel angle position.

Note: For multi-axle vehicles, handling diagrams vary with turn radii (or vehicle speed if the constant speed, variable steer angle test method is used). The turn radius or vehicle speed shall be indicated with each handling diagram, as appropriate for the test method. Alternatively, the effective wheelbase approach described in ISO 14792 may be used to produce handling diagrams that are more similar at different turn radii or vehicle speeds.

(8) Present a graph of understeer/oversteer gradient for the range of lateral acceleration tested. The understeer/oversteer gradient is obtained by subtracting the Ackermann steer angle gradient from the reference steer angle gradient. Using this convention, understeer conditions have positive value and oversteer conditions have negative values. Note- this sign convention contrasts with the gradients observed in the handling diagram.

(9) Present a table indicating the linear range understeer/oversteer gradient (noting the linear range considered), the maximum lateral acceleration achieved, and the limit conditions (understeer, oversteer, or neutral steer), in both turn directions. Report steering sensitivity (in units of $g/(100 \text{ deg } \delta_w)$; see SAE J670) using the understeer/oversteer gradient to determine the highest vehicle speed and corresponding steering-wheel angle attained within the linear range of performance (if this exists) or at 0.3 g . If informative, also present the characteristic speed (for understeering vehicles) and the critical speed for oversteering vehicles (see SAE J670, J266 and J2181 for definitions and calculations).

q. Response Gain.

(1) Present lateral acceleration and yaw response gain results graphically following guidance in SAE International J266 for the Response Gain-Speed Test.

(2) From the graphs of lateral acceleration gain, report (in tabular form) steering sensitivity (in units of $g/(100 \text{ deg } \delta_w)$; see SAE International J670) at a select vehicle speed. It is recommended to use the highest vehicle speed tested at a lateral acceleration level within the linear range of performance observed during the Steady State Circular Test. It may be necessary to report a range of values or mean and standard deviation depending on the results obtained from various test trials.

(3) It is recommend that lateral acceleration and yaw rate response times to ninety percent of the steady-state value be reported in tabular form for select step or ramp input test trails using guidance provided in ISO 7401. If a ramp input is used, note the ramp rate with the results.

r. Transient Response. Refer to ISO 7401.

- s. Emergency Lane Change Test. Narrative presenting maximum drive through speeds of the test vehicle for each test course, along with a description of limit conditions (wheel lift, spin-out, etc.).
- t. Electronic Stability Control. Refer to TOP 02-2-718A.
- u. Lateral Stability of Vehicle Combinations. Refer to ISO 14791.
- v. Control on Adverse Terrain. Narrative presenting observations and evaluations relative to response and control of the vehicle steering system for each terrain condition.
- w. Control on Side Slopes. Narrative describing observations during vehicle operations for each maneuver (i.e., sine wave pattern) on various side slopes.

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APPENDIX A. DEAD ENGINE STEERING COURSE.

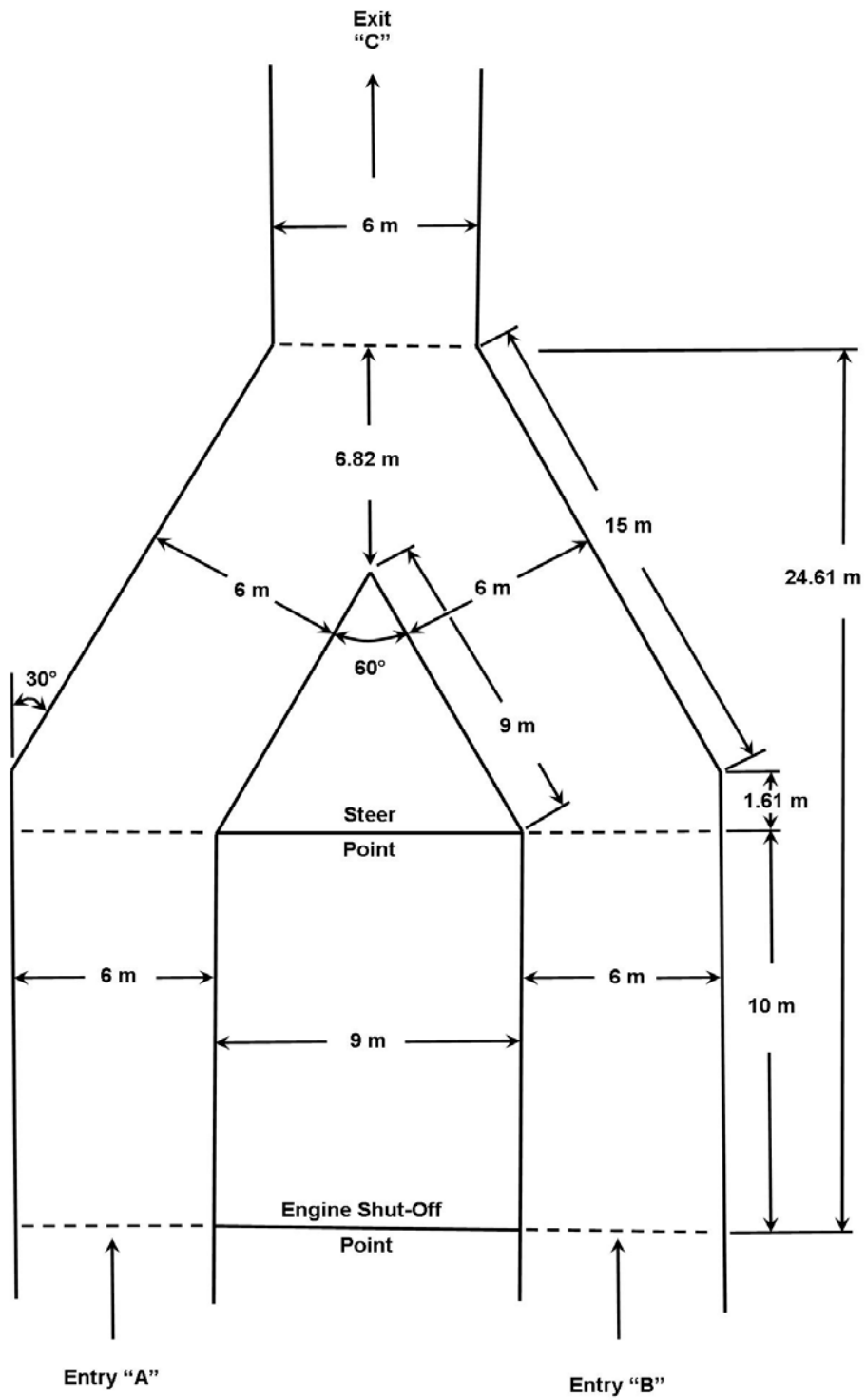


Figure A-1. Typical Dead Engine Steering Course.

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APPENDIX B. TURNING CIRCLE DIAMETERS.

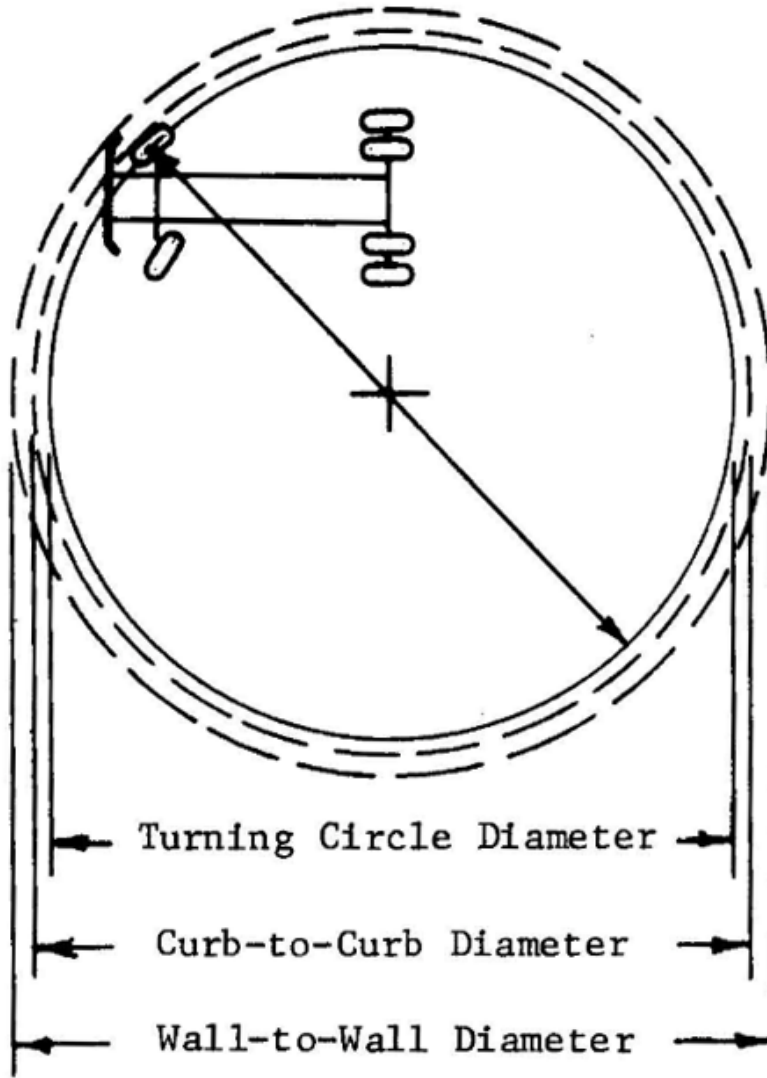
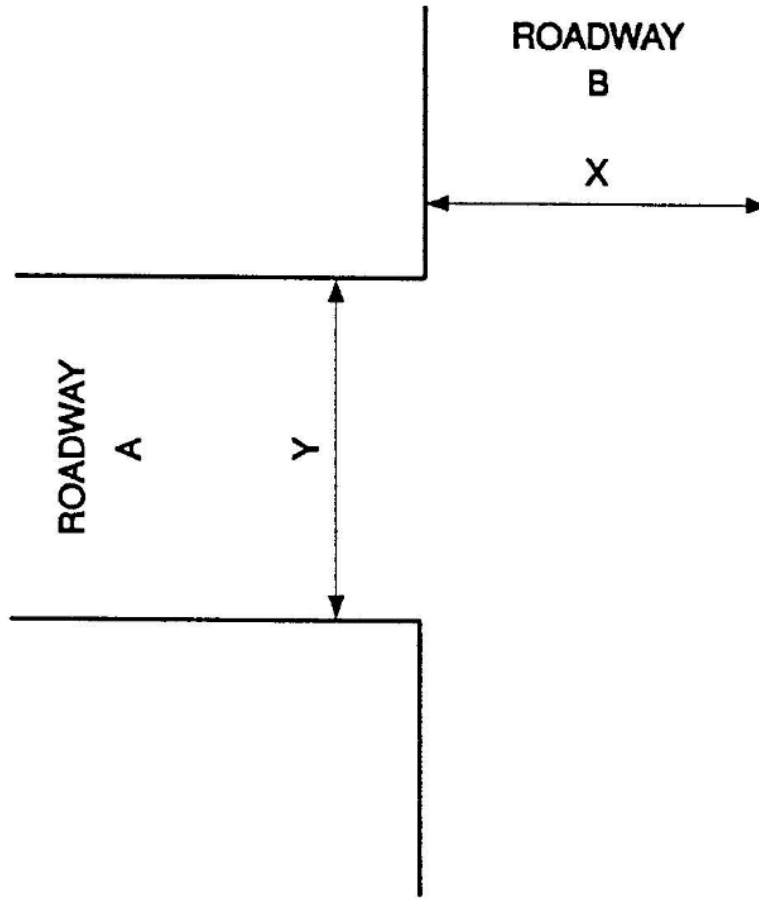


Figure B-1. Turning circle diameters definitions.

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APPENDIX C. MINIMUM ROAD WIDTH FOR T-JUNCTION.

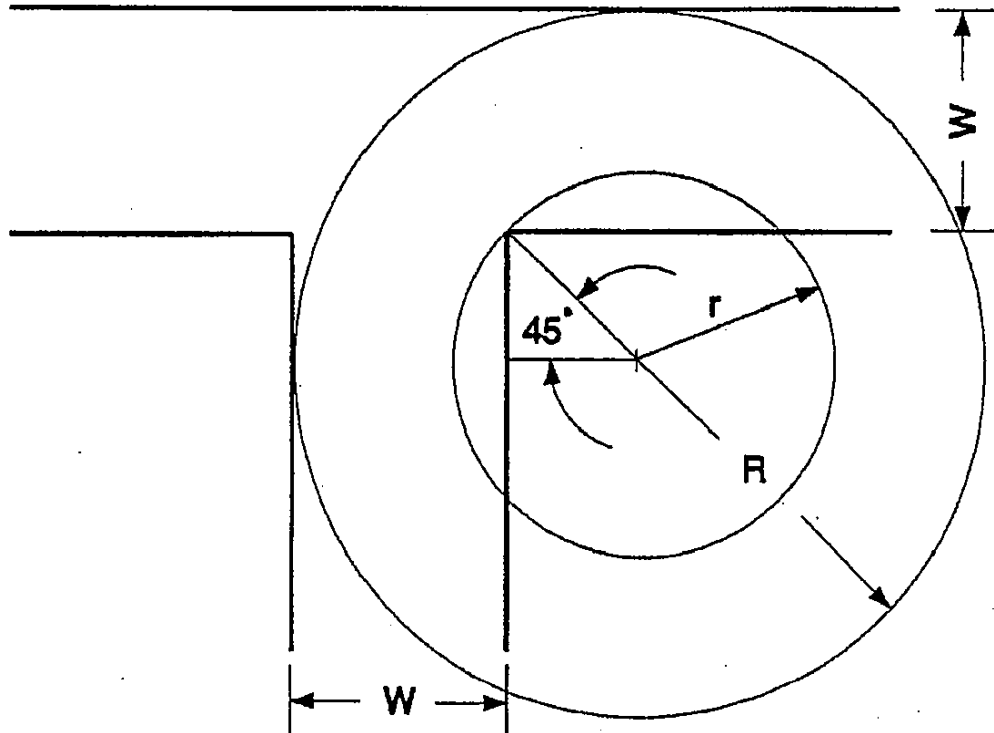


NOTES:

1. X and Y are to be equal.
2. The test result is the minimum value of X and Y which allows the vehicle to negotiate the T-junction in all directions without making contact.

Figure C-1. Minimum Road Width test course.

APPENDIX C. MINIMUM ROAD WIDTH FOR T-JUNCTION.

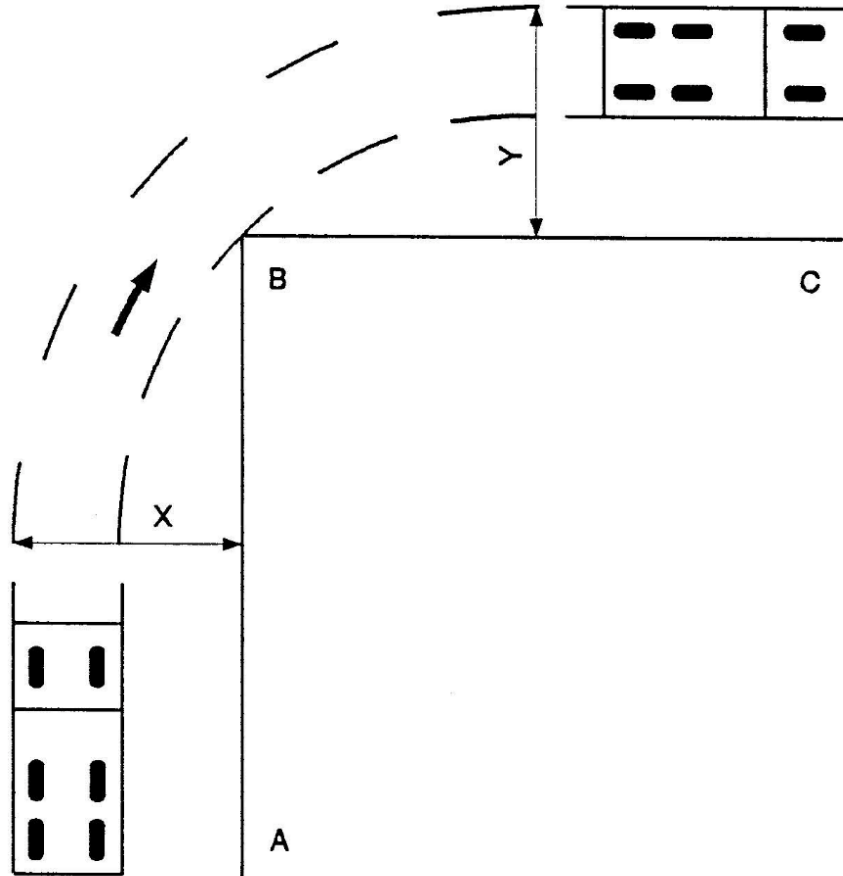


$R = 1/2 \times \text{Outer turning circle diameter}$
 $r = 1/2 \times \text{Inner turning circle diameter}$
 $W = R - (r \times \sin 45^\circ)$
Where $W = \text{Minimum road width of T-junction}$

NOTE: The calculation shall also be performed using the values of r and R for a turning circle in the opposite direction. The higher value of W shall be presented as the result.

Figure C-2. Calculation of minimum road width.

APPENDIX C. MINIMUM ROAD WIDTH FOR T-JUNCTION.



NOTES:

1. Dimension X is the greatest perpendicular distance from line AB to the outer track.
2. Dimension Y is the greatest perpendicular distance from line BC to the outer track.
3. The test is repeated until X and Y approximately agree.
4. The result is the greater of X and Y.

Figure C-3. Practical measurement of minimum road width.

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APPENDIX D. SWEPT PATHS.

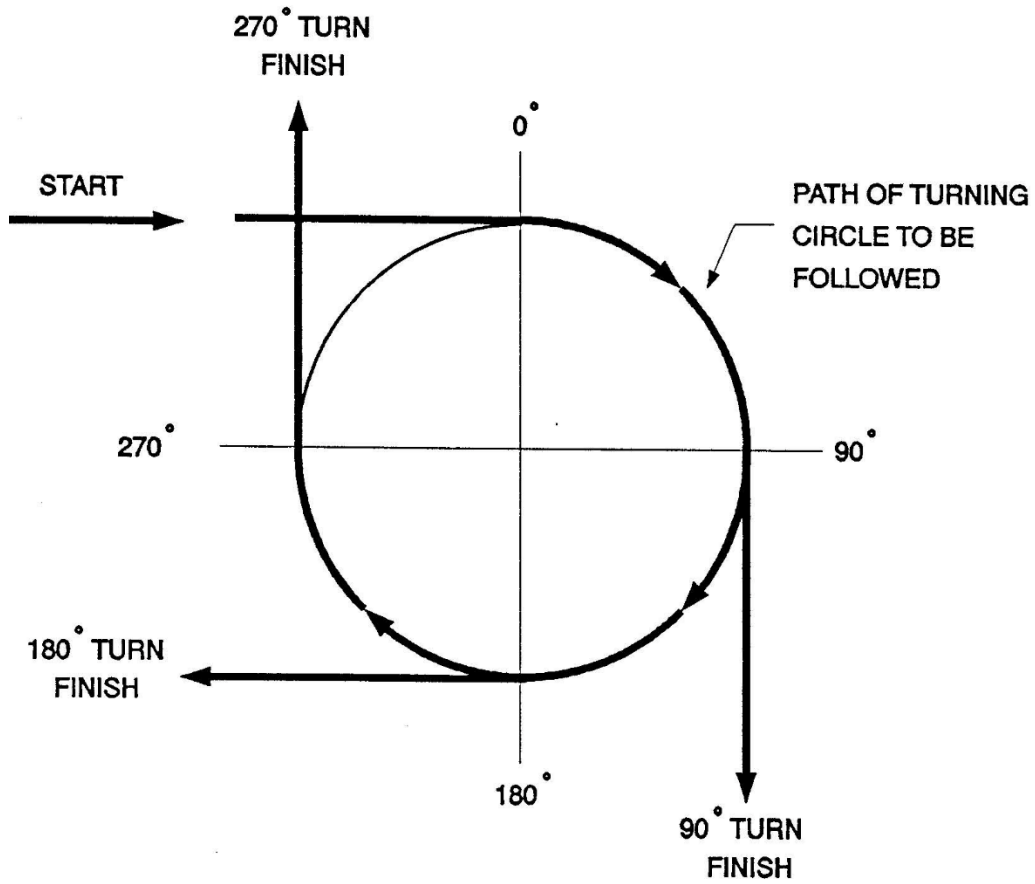


Figure D-1. Vehicle Swept Path Start and Finish Points.

APPENDIX D. SWEEP PATHS.

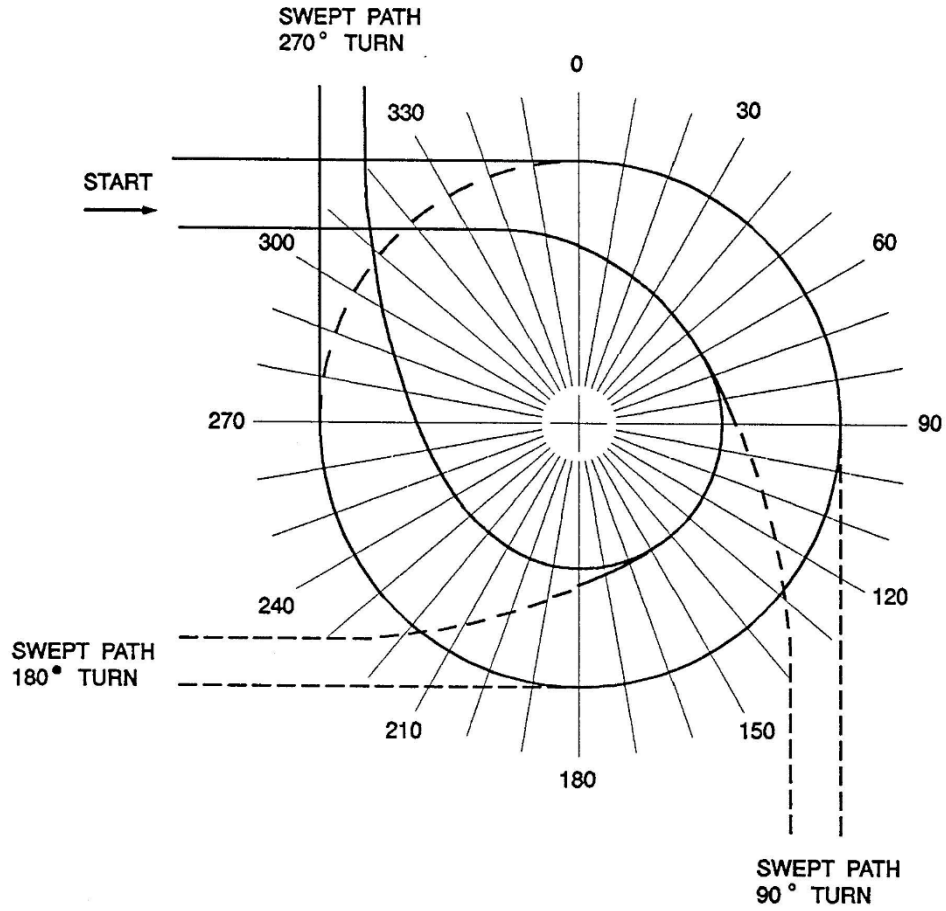


Figure D-2. Typical Swept Path of Vehicle Train for Turns of 90°, 180° and 270° at Constant Turning Circle Diameters.

APPENDIX E. SLALOM COURSES.
(per NATO AVTP 03-30).

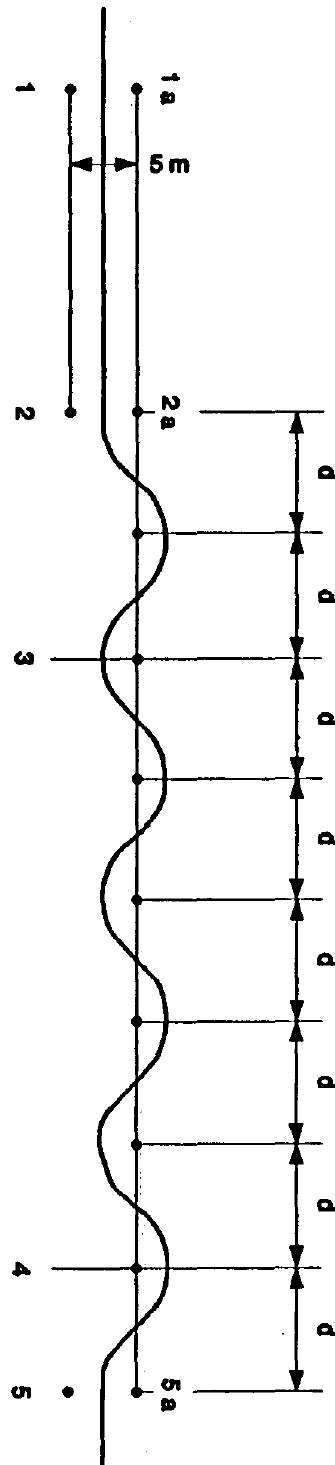


Figure E-1. Constant step slalom course.

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APPENDIX G. STEERING PERFORMANCE TEST COURSE.

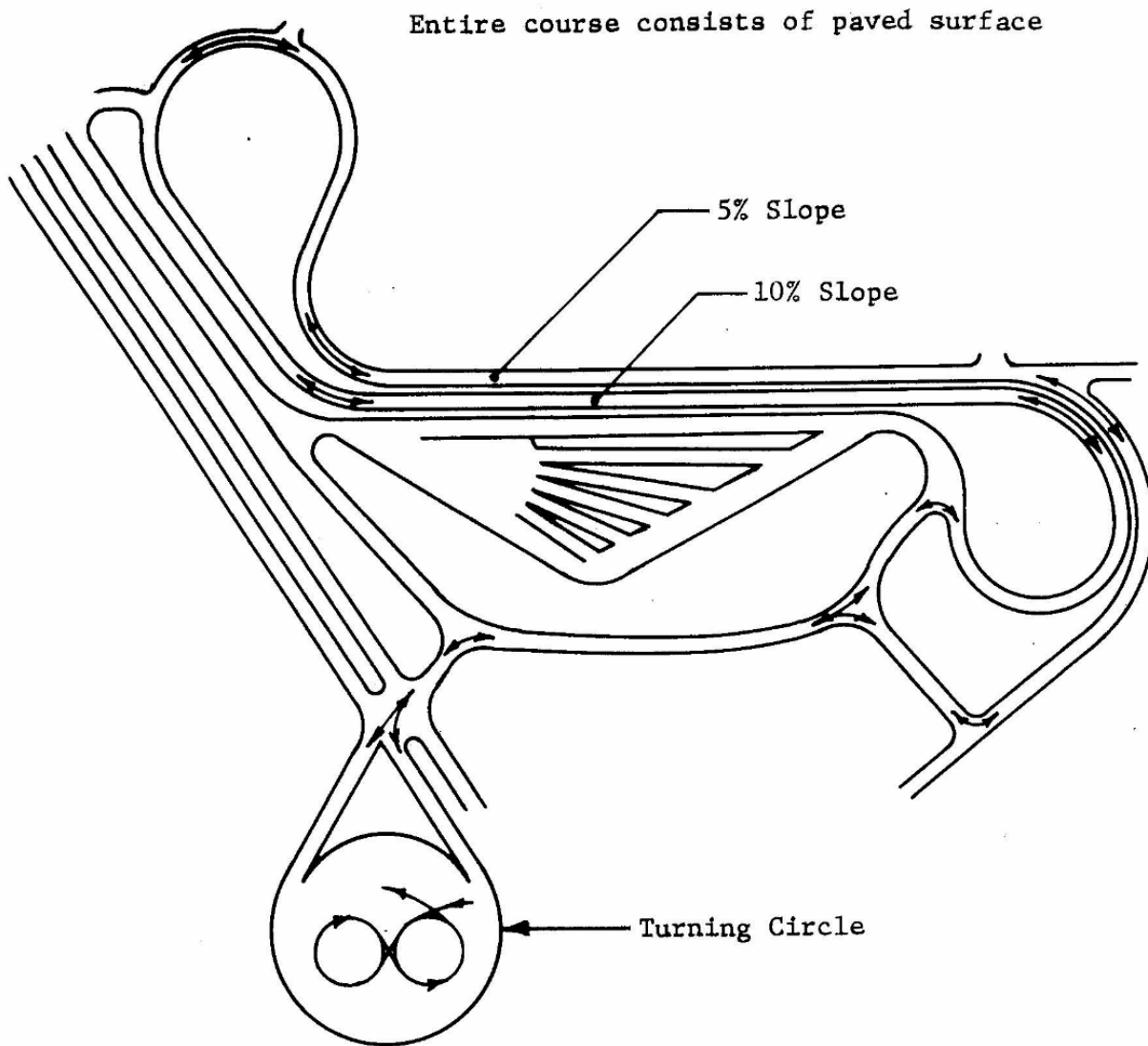


Figure G-1. Steering Performance Test Course, Munson Test Area (MTA), Aberdeen Proving Ground (APG), Maryland.

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APPENDIX H. STEP AND RAMP STEER INPUTS.

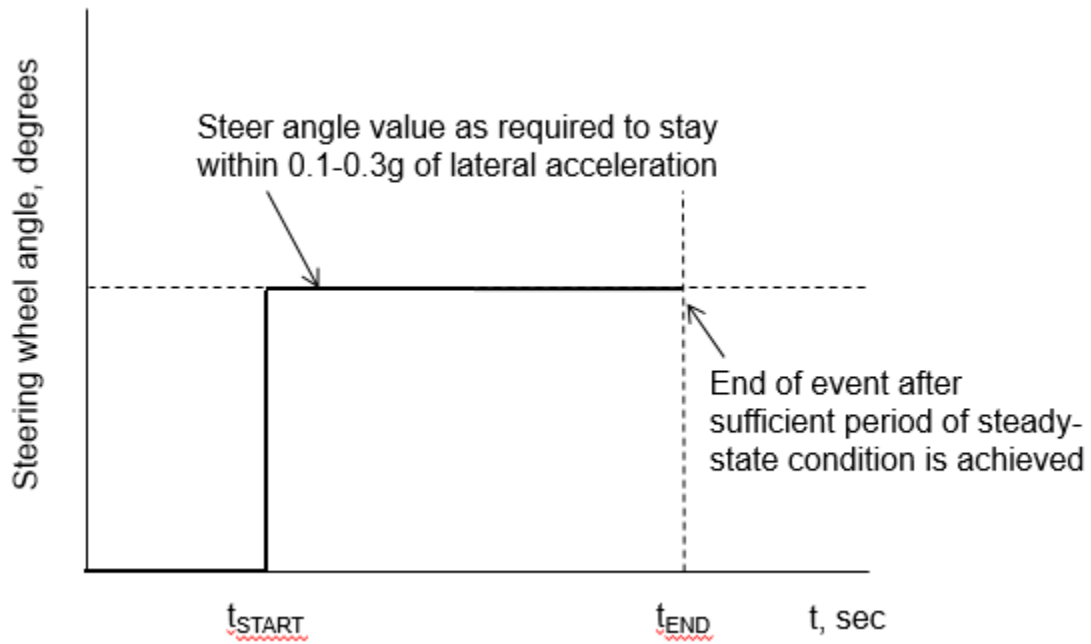


Figure H1. Step-steer input.

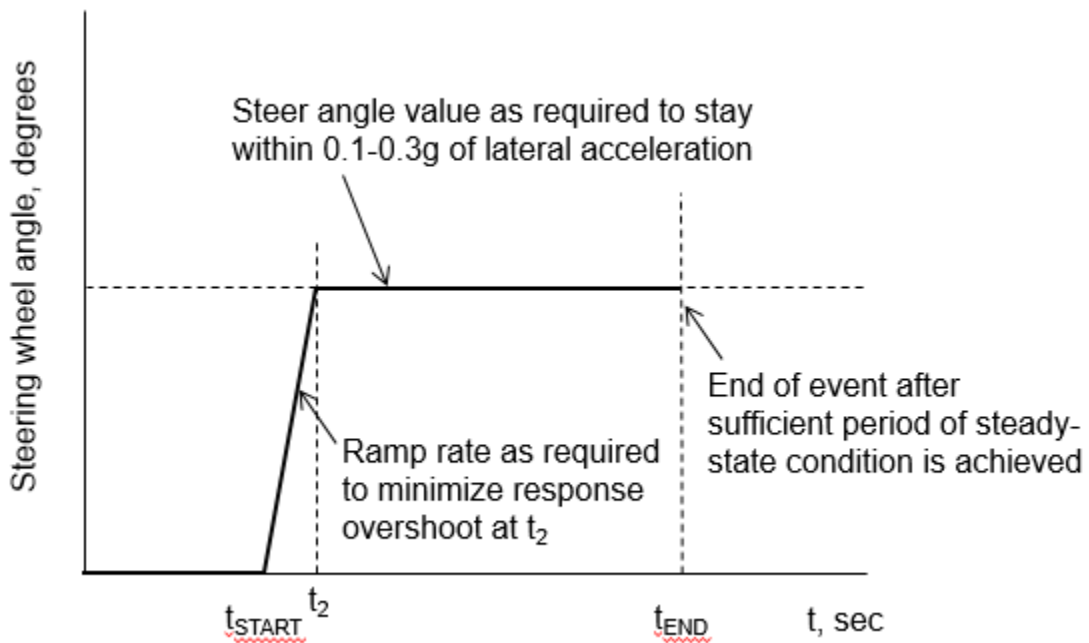
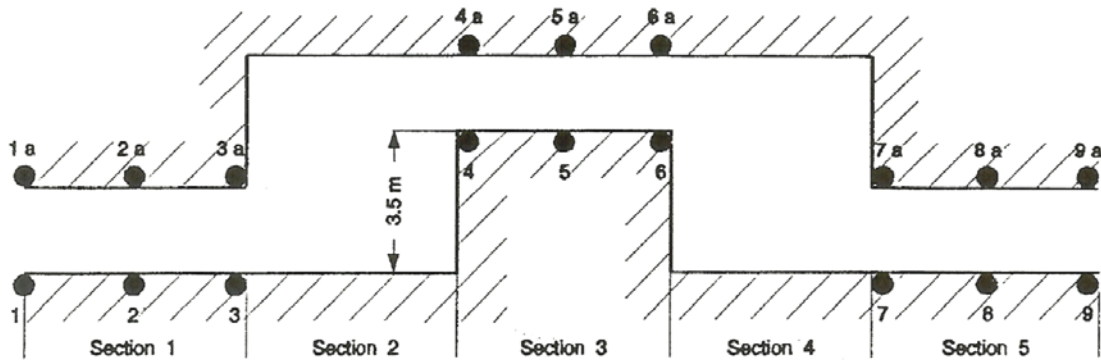


Figure H2. Ramp-steer input.

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APPENDIX I. LANE CHANGE TEST COURSES.



Lane change track dimensions:

Section 1 : Length = 15 m
Width = $1.1 \cdot \text{vehicle width}^a + 0.25 \text{ m}$

Section 2 : Length = Overall length of vehicle^b + 24 m

Section 3 : Length = 25m
Width = $1.2 \cdot \text{vehicle width} + 0.25 \text{ m}$

Section 4 : Length = Overall length of vehicle + 24 m

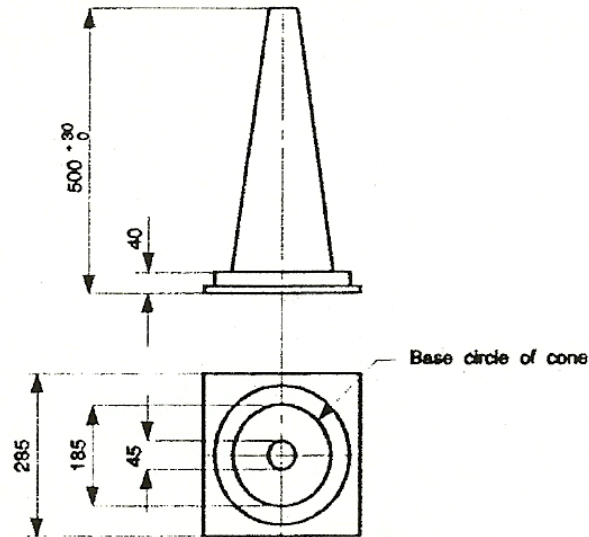
Section 5 : Length = 15 m
Width = $1.1 \cdot \text{vehicle width} + 0.25 \text{ m}$

^a Vehicle dimensions expressed in meters.

^b Overall length of vehicle measured 0.50m from the ground.

Figure I-1. NATO Lane Test Course.

APPENDIX I. LANE CHANGE TEST COURSES.



Note: All dimensions are expressed in millimeters.

Figure I-2. Traffic cone used for lane-change track delineation.

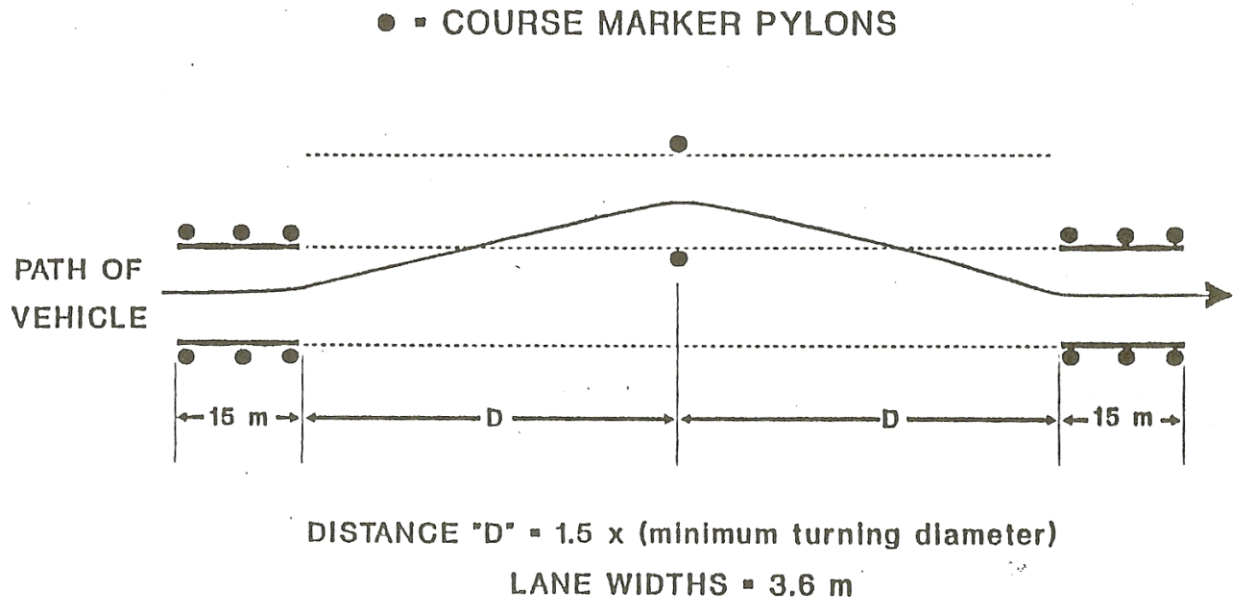


Figure I-3. TOP Lane Change Course.

APPENDIX J. STEERING RATIO PLOTS.

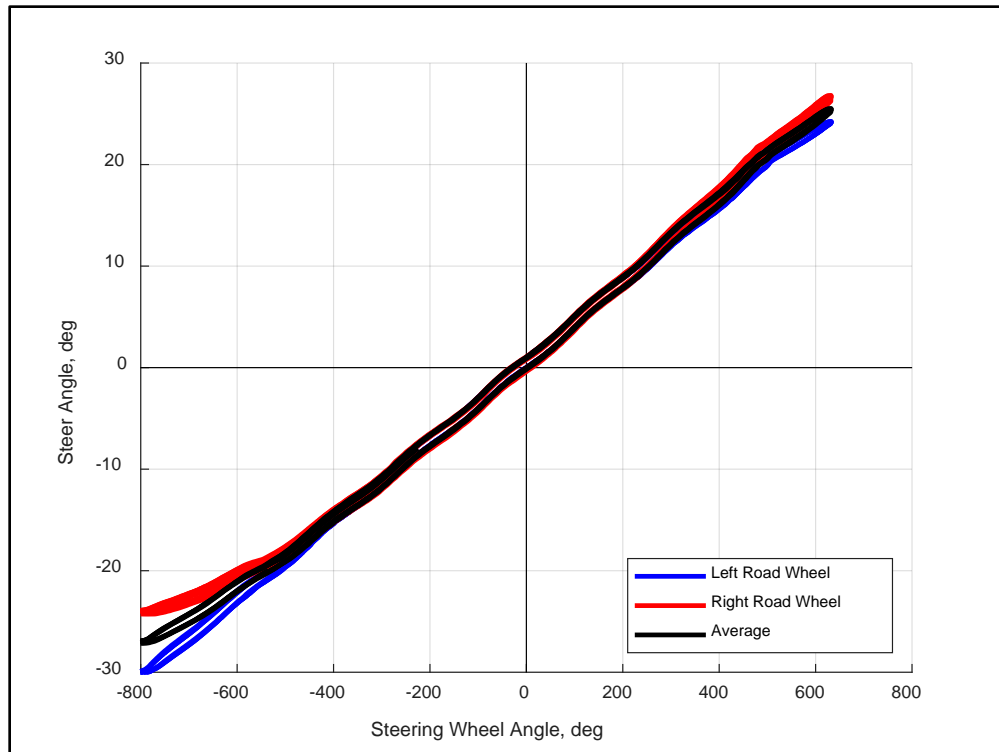


Figure J-1. Wheel angle versus steering wheel angle results.

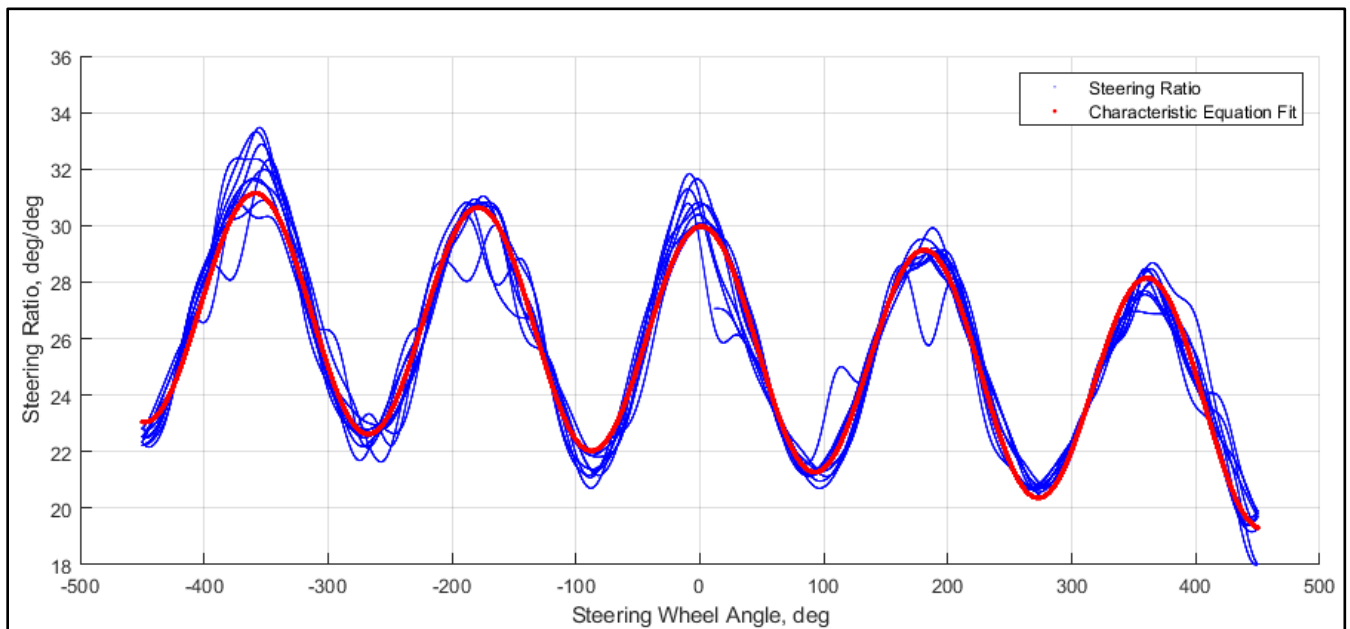


Figure J-2. Steering ratio results.

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APPENDIX K. STEERING CURVE FIT PROCEDURE.

K.1. PREPARATION.

a. The data used for the following procedure were derived from road wheel angles (RWA) data measured using instrumented turn plates. The steering hand wheel angle (SWA) was controlled and measured using a steering robot. Prior to sampling the steering data, the vehicle was driven in a straight line on a road with minimal side slope (down the center of the crown if necessary) to establish a zero-steer condition. The steering robot software calculated the average SWA and established that as the zero point.

b. The front steerable axle of the vehicle was positioned on a pair of instrumented turn plates. The tires on the remaining axles were brought to the same height above the ground plane using spacers beneath the remaining tires. Failure to compensate for the chassis inclination may introduce caster effects into the RWA measurements.

c. The steering robot was programmed with a triangle wave profile starting at zero-steer and cycling between the left and right cramping angles (without contacting the stops) for five complete periods before ending at zero. The steering wheel velocity was set at a constant SWA rate of 50 deg/s.

d. The analysis presented below was based on the use of MATLAB numerical computing software.

K.2. ANALYSIS PROCEDURE.

Step 1. Import the RWA and SWA data into Matlab for processing.

```
chanlist = {...  
    'Steering Wheel Angle',...    1  
    'Left Road Wheel Angle',...   2  
    'Right Road Wheel Angle',...  3  
};
```

Step 2. Digitally filter the data with a 6-pole, 10-Hz low-pass Butterworth filter.

Step 3. Calculate the mean reference steering angle, based on the right and left RWA data.

Step 4. Differentiate the filtered SWA and mean reference steering angle data vectors. For this analysis, the differentiation was done with respect to data samples (deg/sample), not time (deg/sec).

APPENDIX K. STEERING CURVE FIT PROCEDURE.

Step 5. Create an 'inverse steering ratio' data vector by dividing the differentiated SWA data vector by the differentiated mean reference steering angle (termed RWA in the code below) data vector.

Note: This analysis was conducted using the inverse of the steering ratio ($dRWA/dSWA$), not the true steering ratio ($dSWA/dRWA$).

Step 6. Remove data near the start/end conditions by eliminating these data based on steering wheel angle at the beginning and end of the data set. The data removals improve the curve fit model in the area of interest.

Step 7. Digitally filter the resulting inverse steering ratio vector. Sample Matlab functions for Steps 3 through 7 are shown below. The ButterFilter2 function called at the end of the steps is not shown for brevity, but is a simple 6-pole, 10-Hz low-pass Butterworth filter.

```
SWA = data(1).values;
dSWA = diff(SWA);
RWA = mean([data(2:3).values], 2);
dRWA = diff(RWA);
ratio = dRWA./dSWA;
SWA = SWA(2:end); %Makes SWA the same size as ratio
JunkL = dSWA < 0.097 | dSWA > 0.103 | SWA < -500 | SWA > 500;
SWA = SWA(~JunkL);
ratio = ratio(~JunkL);

ratio = ButterFilter2(ratio, 6, 1, SR(2));
```

Step 8. Fit a second-order polynomial curve to the inverse steering ratio data. The polynomial curve fit is shown in Figure K-1.

```
%% Fit Basic Terms
% A0 + A1*SWA + A2*SWA^2
P1 = polyfit(SWA, ratio, 2); % Polynomial terms
BTF = polyval(P1, SWA); % Basic Term Fit
plot(SWA, BTF, 'r. '); % Plot curve
title('Basic Terms')

A0 = P1(3); A1 = P1(2); A2 = P1(1); % Assign polynomial terms
```

APPENDIX K. STEERING CURVE FIT PROCEDURE.

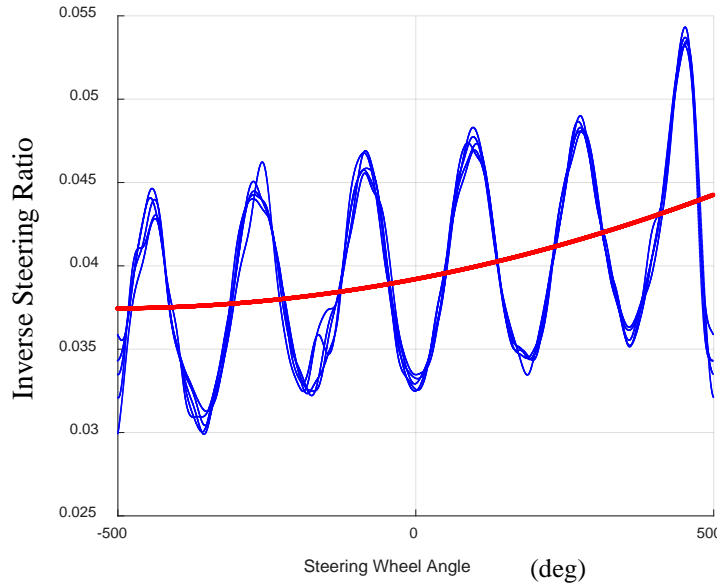


Figure K-1. Inverse steering ratio data and polynomial curve fit.

Step 9. Subtract the resulting polynomial data vector from the inverse steering ratio data vector, to generate a new vector showing only the oscillatory component of the inverse steering ratio data vector. This new vector is called ‘Ratio’ (see Step 10). The oscillatory component is due to the use of universal joints on the intermediate shaft of the steering system. This example shows a fairly extreme case of oscillatory motion.

Step 10. Perform a curve fit to the oscillatory component data vector using MATLAB’s `fminsearch` function. The oscillatory component of the data will be modeled using Equation K-1.

$$B * \cos\left(2 * (SWA - C) * \left(\frac{\pi}{180}\right)\right) \quad \text{Equation K-1}$$

Create an anonymous function (fISP, function: Intermediate Shaft Phasing) to define the form of the R^2 residual error for Equation K-1, as shown in Equation K-2.

$$\sum \left(Ratio - B * \cos\left(2 * (SWA - C) * \left(\frac{\pi}{180}\right)\right) \right)^2 \quad \text{Equation K-2}$$

where; Ratio is the vector described in Step 9.

APPENDIX K. STEERING CURVE FIT PROCEDURE.

The MATLAB code below shows the `fminsearch` process. The variable `(x)` represents the coefficients being solved for, namely a two-element array representing the coefficients `[B, C]` from Equation K-1. An initial guess for `B` and `C` are stored in `xguess` and then read to `fminsearch`. The function `Optimset` is used to specify options for the `fminsearch` execution. Finally, `fminsearch` is called, returning the optimized values for `B` and `C`. The coefficients `B` and `C` are then plugged into Equation K-1 to create vector `ISPTF` (Intermediate Shaft Phasing Term Fit).

```
%% Fit Intermediate Shaft Phasing
% B*cos(2*(SWA-C)*(pi/180))
figure(2); hold on;
fISP = @(x) sum(((ratio-BTF)-(x(1)*cos(2*(SWA-x(2))*(pi/180))))).^2);
xguess = [0.01, 25];
options = optimset('PlotFcns',@optimplotx, 'TolX', 1e-8, 'TolFun', 1e-8);
P2 = fminsearch(fISP, xguess, options);
B = P2(1); C = P2(2);
ISPTF = B*cos(2*(SWA-C)*(pi/180));
```

Step 11. The polynomial curve fit vector and the `ISPTF` vector were added together to create the overall characteristic curve fit of the inverse steering ratio data shown in Figure K-2

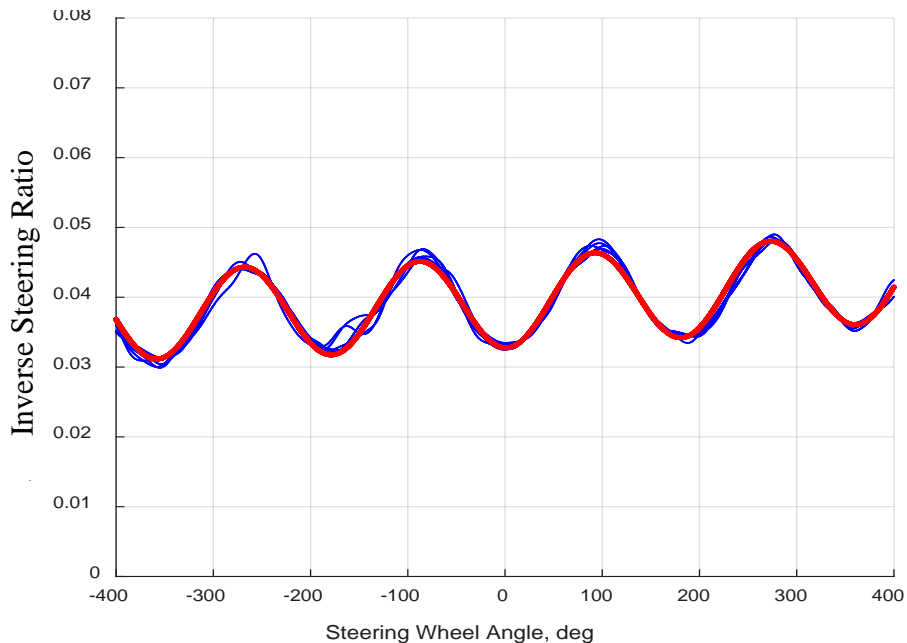


Figure K-2. Inverse steering ratio curve fit.

APPENDIX L. STEERING EFFORT PLOT EXAMPLES.

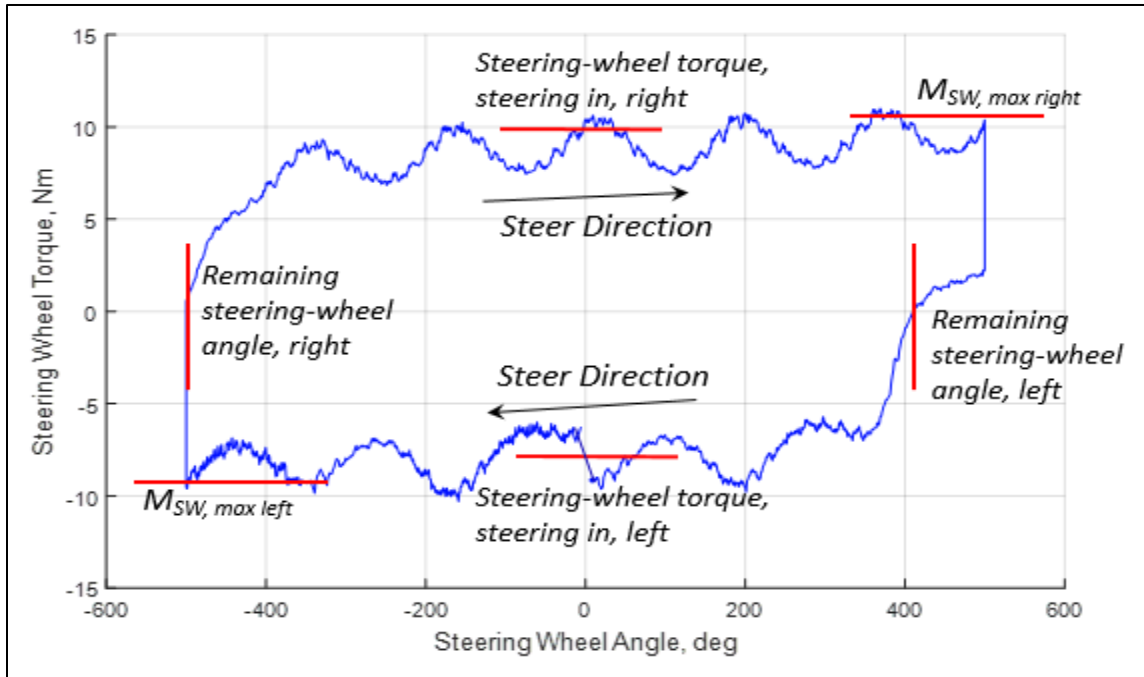


Figure L-1. Steering torque versus steering-wheel angle plot example, showing characteristic values.



Figure L-2. Steering-wheel work characteristic value examples.

APPENDIX L. STEERING EFFORT PLOT EXAMPLES.

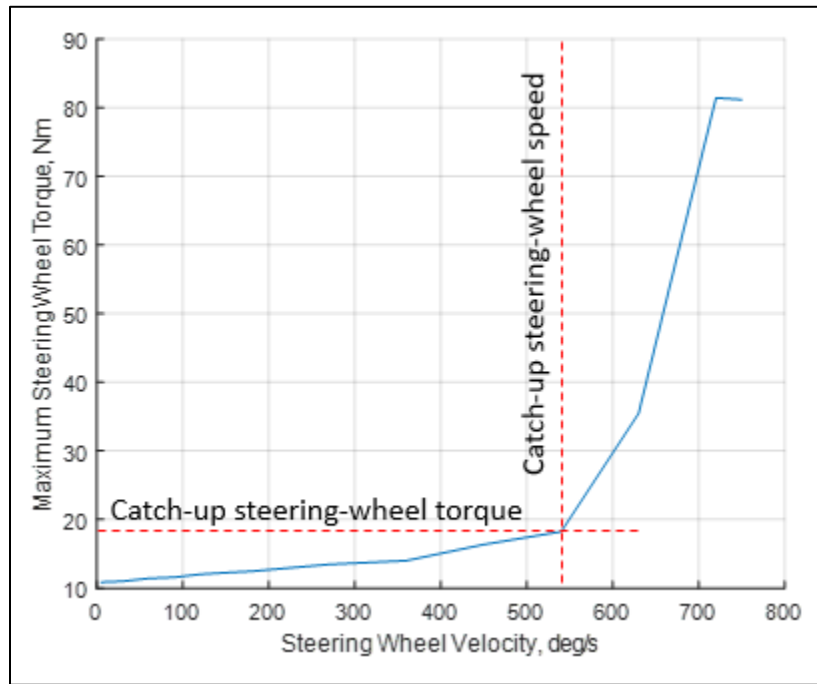


Figure L-3. Maximum torque versus steering-wheel angle speed, showing catch-up speed and torque.

APPENDIX M. ABBREVIATIONS.

APG	Aberdeen Proving Ground
ASTM	American Society for Testing and Materials
ATC	U.S. Army Aberdeen Test Center
AVTP	Allied Vehicle Test Publication
°C	degrees Celsius
CCDC	U.S. Army Combat Capability Development Center
CG	center of gravity
deg/sec	degrees per second
ECP	entry control point
ESC	electronic stability control
GVSC	Ground Vehicle Systems Center
GVW	gross vehicle weight
Hz	Hertz
IMU	inertial measurement unit
ISO	International Organization for Standardization
ISPTF	Intermediate Shaft Phasing Term Fit
K&C	kinematics and compliance
km/hr	kilometers per hour
m/s	meters per second
m	meter
MIL-STD	Military Standard
mph	miles per hour
MTA	Munson Test Area
N	Newton
RWA	road wheel angle
RWS	Roadway Simulator
SAE	Society of Automotive Engineers
SIS	slowly increasing steer
SOP	Standard Operating Procedure
SSF	static stability factor
SWA	steering hand wheel angle

APPENDIX M. ABBREVIATIONS.

TM	Technical Manual
TOP	Test Operations Procedure

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APPENDIX O. APPROVAL AUTHORITY.

CSTE-CI

25 September 2019

MEMORANDUM FOR

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

SUBJECT: Test Operations Procedure 02-2-002A Steering and Cornering Behavior,
Approved for Publication

1. Test Operations Procedure (TOP) 02-2-002A Steering and Cornering Behavior, 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. The scope of the document is as follows:

This TOP prescribes procedures for analyzing the steering and cornering behavior of vehicles and vehicle combinations. The tests described encompass turn ability, maneuverability, response to steady-state and transient steer inputs, handling, directional stability, roll stability, vehicle controllability, accident avoidance maneuver performance, and electronic stability control systems. Pertinent automotive industry standards are referenced for terminology and test methods.

2. This document is approved for publication and will be posted to the Reference Library of the ATEC Vision Digital Library System (VDLS). The VDLS website can be accessed at <https://vdl.s.atc.army.mil/>.

3. Comments, suggestions, or questions on this document should be addressed to U.S. Army Test and Evaluation Command (CSTE-TM), 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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Director, Directorate for Capabilities
Integration (DCI)

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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: Automotive Instrumentation Division (TEDT-AT-ADI), U.S. Army Aberdeen Test Center, 6943 Colleran Road, Aberdeen Proving Ground, MD 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.