Chapter 6: System Testing

This chapter presents a comprehensive overview of the system-level testing procedures conducted for the autonomous vehicle software developed in this project. The primary objective of system testing is to verify the end-to-end functionality, robustness, and safety of the autonomous system in real-world scenarios. Our approach ensures that the software components function cohesively, meeting both user requirements and safety standards for personal autonomous vehicle systems.

6.1 Objectives of System Testing

The objectives of system testing in this project are:

6.1.1 **Validate Functional Requirements**: Ensure that all components work together to meet specified functionalities, such as navigation, obstacle avoidance, and traffic light recognition.

6.1.2 **Safety and Reliability Testing**: Test the system’s response to hazardous situations, such as obstacle detection failures or adverse weather conditions.

6.1.3 **Performance and Environmental Testing**: Assess the system’s capability under various environmental conditions to ensure reliability in practical usage.

6.1.4 **Simulation Integration Testing**: Validate the interaction between ROS Noetic and the CARLA simulator, ensuring accurate data exchange and feedback.

6.2 System Testing Methodology

We adopted a rigorous, systematic testing approach tailored to the specifics of our autonomous vehicle software. Given the complexity and safety-critical nature of autonomous systems, we utilized a **black-box testing methodology**. This approach focuses on evaluating the system's external behavior without requiring knowledge of its internal workings, ensuring that the software meets the specified requirements from an end-user perspective. The methodology involved creating realistic test scenarios using the CARLA simulator, setting up test cases for each subsystem, and observing the interactions between components.

6.3 Functional System Test Cases

This section documents the functional system test cases, focusing on core functionalities like navigation, traffic light detection, and obstacle avoidance.

6.3.1 Path Planning

Equivalence Class Partitioning (ECP):

- **Valid Classes**:
  - The destination is selected from the provided options.
  - The destination is entered manually and is valid (x is integer, y is integer).

- **Invalid Classes**:
  - The destination is selected but is not available (e.g., out of service area).
  - The destination coordinates are entered manually but are invalid (e.g., incorrect format, non-existent location).

Test Case:

Table 6.1: Black Box TC1

Scenario	Input Value	ECP	Expected Output
User enters the destination from given destinations	Home	Valid	Vehicle navigates successfully to the entered destination.
User enters the destination from given destinations	x = -60.000000 y = 60.000000	Valis	Vehicle navigates successfully to the entered destination.

6.3.2 Path Following

Equivalence Class Partitioning (ECP):

- **Valid Classes**:
  - The vehicle's velocity and acceleration parameters are within normal operational ranges. i.e. <120 km/h
- **Invalid Classes**:
  - The vehicle's velocity or acceleration parameters are abnormal or invalid. i.e. = 120km/h

Test Cases:

Table 6.2: Black Box TC2

Scenario	Input Value	ECP	Expected Output
Normal Velocity Parameters	Velocity = 200 km/h	Valid	Vehicle accelerates smoothly within limits and maintains a steady trajectory

6.3.3 Vehicle Control

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - The vehicle's speed is within the normal operational range (i.e. 0 km/h to maximum speed limit).
  - The throttle position is within the normal operational range (i.e. 0% to 100%).
- **Invalid Classes:**
  - The vehicle's speed parameters are abnormal or invalid (i.e. speed exceeding maximum permissible limit).
  - The throttle position is abnormal or invalid (i.e. throttle position exceeding 100%).

Test Cases:

Table 6.3: Black Box TC3

Scenarios	Input Value	ECP	Expected Output
Normal Speed	Speed = 50 km/h	Valid	Vehicle operates smoothly at the given speed.
Normal Throttle Position	Throttle = 50%	Valid	Vehicle accelerates normally without issues.

6.3.4 Vehicle Control

Equivalence Class Partitioning (ECP):

- **Valid Classes:**

  Normal Steering: Steering angle within operational range
  - -90° to 90° latitude, -180° to 180° longitude
- **Invalid Classes:**

  Abnormal Steering: Steering angle outside operational range (< -30° or > +30°)

Test Cases:

Table 6.4: Black Box TC4

Scenarios	Input Value	ECP	Expected Output
Normal Orientation	Roll = 10° Pitch = 5°	Valid	Vehicle maintains stable orientation.
Acceptable Steering Angle	Angle = 15°	Valid	Vehicle steers appropriately without error.

6.3.5 Vehicle Control

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Speed: 0 km/h ≤ Speed ≤ 120 km/h
  - Distance: 2 meters ≤ Distance ≤100 meters
  - Throttle Adjustment: 0 % ≤ Throttle ≤ 80 %
  - Brake Application: 0 % ≤ Braking Force ≤ 100 %
- **Invalid Classes:**
  - Speed: > 120 km/h
  - Distance: Distance >100 meters
  - Throttle Adjustment: < 0 % or Throttle > 80 %
  - Brake Application: < 0 % or Braking Force > 100 %

Test Cases:

Table 6.5: Black Box TC5

Scenarios	**Input Value**	**ECP**	**Expected Output**
Normal Speed	Speed = 100 km/h	Valid	Vehicle operates efficiently within speed limits.
Safe distance	Distance = 50 meters	Valid	Vehicle maintains safe distance without issue.
Acceptable Throttle	Throttle = 60%	Valid	Vehicle accelerates smoothly as expected.
Normal Brake Application	Force = 75%	Valid	Vehicle decelerates smoothly without issues.

6.3.6 Vehicle Control

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Lateral Position: -1.0 meters ≤ Lateral Position ≤ 1.0 meters
  - Steering Adjustment: -30° ≤ Steering Angle ≤30°
- **Invalid Classes:**
  - Lateral Position: Lateral Position > 1.0 meters
  - Steering Adjustment: Steering Angle > 30°

Test Cases:

Table 6.6: Black Box TC6

Scenarios	Input Value	ECP	Expected Output
Valid Lateral Position	Lateral Position = 0.5 meters	Valid	Vehicle maintains intended lane position.
Normal Steering Adjustment	Angle = 15°	Valid	Vehicle steers correctly without issue.

6.3.7 Localization Module Test Cases

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Sensor data (GPS, IMU, LIDAR) within acceptable ranges.
  - GPS accuracy ≤ 5 meters.
  - IMU data drift ≤ 2 degrees.
  - LIDAR scan range ≥ 50 meters.
- **Invalid Classes:**
  - Sensor data outside acceptable ranges.
  - GPS accuracy > 5 meters.
  - IMU data drift > 2 degrees.
  - LIDAR scan range < 50 meters.

Test Cases:

Table 6.7: Black Box TC7

Scenario	Input Value	ECP	Expected Output
Accurate GPS Signal	GPS Accuracy = 3 meters	Valid	Vehicle update's location correctly.
Valid IMU Data	IMU Drift = 1 degree	Valid	Vehicle continues to maintain accurate positioning.
Adequate LIDAR Scan Range	LIDAR Range = 60 meters	Valid	Vehicle successfully detects surroundings.

6.3.8 Obstacle Detection and Avoidance Module Test Cases

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Obstacle detected within sensor range.
  - LIDAR detection distance ≤ 100 meters.
  - Obstacle size ≥ 0.5 meters.
  - Obstacle-free zone.
  - No objects detected within 100 meters.
- **Invalid Classes:**
  - Sensor fails to detect within expected range.
  - LIDAR detection distance > 100 meters for a detected obstacle.
  - Obstacle size < 0.5 meters considered noise.

Test Cases:

Table 6.8: Black Box TC8

Scenario	Input Value	ECP	Expected Output
No Obstacle Detected	LIDAR Detection Distance = 150 meters	Valid	Vehicle proceeds without any detection issues.
Valid Obstacle Detected	LIDAR Detection Distance = 50 meters	Valid	Vehicle transitions to classify detected obstacle.
Clear Path Ahead	LIDAR Detection Distance = 80 meters	Valid	Vehicle successfully computes navigation path.

6.3.9 Traffic Light Detection Module Test Cases

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Traffic light detected and state correctly identified.
  - Distance to traffic light ≤ 50 meters.
  - Recognition confidence ≥ 80%.
- **Invalid Classes:**
  - Traffic light detection errors or low recognition confidence.
  - Distance to traffic light > 50 meters.
  - Recognition confidence < 80%.

Test Cases:

Table 6.9: Black Box TC9

Scenario	Input Value	ECP	Expected Output
Traffic Light Detected	Detection Distance = 30 meters	Valid	Vehicle identifies traffic light state correctly.
Traffic Light Detected, High Confidence	Recognition Confidence = 90%	Valid	Transition to Recognize State
Low Confidence in Recognition	Recognition Confidence = 70%	Invalid	Re-scan for traffic light state
Traffic Light at Threshold	Detection Distance = 50 meters	Valid	Proceed with state recognition (Red/Yellow/Green)

6.3.10 Functional Requirement Testing

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Destination coordinates within defined boundaries and obstacles.
  - Setpoints defined and within ±0.5 meters of the planned path.
  - Traffic light present and recognized properly.
  - Obstacle within detection range and accurately identified.

- **Invalid Classes:**
    - Destination coordinates outside operational boundaries or near non-navigable areas.
    - Setpoints defined with deviations greater than ±0.5 meters from the planned path.
    - No traffic light present or misidentified state (e.g., recognition error).
    - Obstacle detected outside the 5-meter range or misclassified as safe.

Test Cases:

Table 6.10: Black Box TC10

Scenario	Input/Conditions	ECP	Expected Outcome
Path planning to destination	Input destination coordinates	Valid	Vehicle plans a feasible route considering obstacles and road boundaries
Path following accuracy	Input setpoints for route	Valid	Vehicle follows the planned path accurately within ±0.5 meters deviation
Traffic light detection	Approach intersection with traffic light	Valid	Vehicle detects traffic light state and acts accordingly (stop/go)
Obstacle detection and avoidance	Obstacle within 5 meters ahead	Valid	Vehicle decelerates and navigates around obstacle safely

6.4 Safety and Hazard Response Testing

Testing the system’s response to hazardous scenarios ensures that the vehicle can handle safety-critical situations without compromising passenger safety.

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
    - Sensors functioning normally, detection within acceptable limits
    - Rain simulation executed without sensor errors.
    - GPS operational, providing accurate positioning data.
    - Obstacles detected within the specified range.
- **Invalid Classes:**
    - Sensor failure not triggering safe mode or alerts.
    - Vehicle fails to adjust speed or braking distance during heavy rain.

- GPS failure leading to a localization error without fallback.
- Emergency braking not performed within 1 meter or failure to detect obstacle.

Test Cases:

Table 6.11: Black Box TC11

Scenario	Input/Conditions	ECP	Expected Outcome
Obstacle detection failure	Simulated sensor failure	Valid	Vehicle enters safe mode, slows down, and alerts user
Adverse weather (rain simulation)	Heavy rain simulation in CARLA	Valid	Vehicle adjusts speed, increases braking distance
GPS signal loss	Disable GPS in CARLA	Valid	System initiates localization using IMU and LIDAR data
Emergency braking	Immediate obstacle within 2 meters	Valid	Vehicle performs emergency brake within 1 meter distance

6.5 Performance Testing

Performance testing evaluates the system’s responsiveness, computational efficiency, and resource usage to ensure it meets operational requirements.

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - System response time meets specified performance criteria.
  - System resource usage remains under limits during full load.
  - Localization accuracy is maintained within ±2 meters.
- **Invalid Classes:**
  - Response time exceeds 0.5 seconds for obstacle detection.
  - CPU or memory usage exceeds acceptable limits (>80%).
  - Localization accuracy exceeds ±2 meters from input coordinates

Test Cases:

Table 6.12: Black Box TC12

Scenario	Input/Conditions	ECP	Expected Outcome
Response time for obstacle detection	Moving obstacle appears within range	Valid	System detects and begins avoidance maneuver within 0.5 seconds

Computational load	Full system simulation with all modules active	Valid	CPU and memory usage within acceptable limits (<80%)
Localization accuracy	Test using varied GPS coordinates	Valid	Vehicle stays within ±2 meters accuracy to input coordinates

6.6 Environmental Testing

Environmental testing assesses the system's reliability and response under various simulated weather conditions, including rain, fog, and low visibility.

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Vehicle responds appropriately to fog conditions.
  - Vehicle adapts correctly to night driving conditions.
  - Vehicle maintains safe operation during heavy rain.
- **Invalid Classes:**
  - Vehicle fails to slow down or activate fog lights in fog.
  - Vehicle does not adjust to reduced visibility.
  - Vehicle does not adjust speed or distance during heavy rain.

Test Cases:

Table 6.13: Black Box TC13

Scenario	Input/Condition	ECP	Expected Outcome
Fog simulation	High-density fog in CARLA	Valid	Vehicle slows to maintain safe distance, activates fog lights
Night-time driving	Night mode with reduced lighting	Valid	Vehicle adjusts to reduced visibility, activates headlights
Heavy rain	Rain simulation	Valid	Vehicle adjusts speed, maintains safe distance from other objects

6.7 Simulation Integration Testing

Testing integration between CARLA and ROS is critical for verifying that the data exchange is accurate and that system responses reflect real-time simulation inputs.

Equivalence Class Partitioning (ECP):

- **Valid Classes:**
  - Accurate and timely data exchange occurs between CARLA and ROS.
  - Command successfully transmitted and executed.
  - Continuous feedback allows for effective vehicle control adjustments.
- **Invalid Classes:**
  - Data exchange delayed or inaccurate.
  - Command transmission fails to stop the vehicle.
  - Feedback loop not resulting in smooth control transitions.

Test Cases:

Table 6.14: Black Box TC14

Scenario	Input/Conditions	ECP	Expected Outcome
CARLA-ROS data exchange	Position and velocity data updates	Valid	ROS receives accurate, real-time data from CARLA without delay
Action command transmission	Send stop command to CARLA vehicle	Valid	CARLA vehicle stops immediately on command
Feedback loop validation	Continuous commands based on feedback	Valid	Smooth transitions and adjustments in vehicle control