POLITECNICO DI MILANO

SOFTWARE ENGINEERING 2 - PROJECT 2025-2026

Best Bike Paths (BBP)

Requirement Analysis and Specification Document

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January 30, 2026

Contents

1 Introduction **5**
1.1 Purpose 5
1.2 Scope 5
1.2.1 World Phenomena 5
1.2.2 Shared Phenomena 5
1.3 Definitions, Acronyms, and Abbreviations 6
1.3.1 Definitions 6
1.3.2 Acronyms and Abbreviations 6
1.4 Revision History 7
1.5 Reference Documents 7
1.6 Document Structure 7

2 Overall Description **9**
2.1 Product Perspective 9
2.1.1 Scenarios 9
2.1.2 Domain Class Diagram 15
2.1.3 State Machine Diagram 16
2.1.4 System Interfaces 18
2.2 Product Functions 18
2.2.1 User Account Management 18
2.2.2 Trip Management (Registered Users Only) 19
2.2.3 Data Acquisition & Reporting 19
2.2.4 Visualization & Routing 19
2.2.5 Data Processing (Server Side) 20
2.3 User Characteristics 20
2.3.1 Registered Users 20
2.3.2 Unregistered Users (Guests) 21
2.3.3 Usage Environment 21
2.4 Assumptions, Dependencies, and Constraints 21
2.4.1 Assumptions 21
2.4.2 Dependencies 21
2.4.3 Constraints 22

3 Specific Requirements **23**
3.1 User Interfaces 23
3.1.1 Onboarding and Main Dashboard 23
3.1.2 Reporting and Verification 24
3.2 Hardware Interfaces 24
3.3 Software Interfaces 25
3.4 Functional Requirements 26
3.4.1 Data Requirements & Classification 26
3.4.2 Use Case Diagram 26
3.4.3 Detailed Use Cases 27
3.4.4 Sequence Diagrams 30
3.4.5 Requirements Mapping 33
3.5 Performance Requirements 33
3.5.1 Latency and Response Time 33
3.5.2 Accuracy and Precision 34
3.5.3 Resource Usage (Battery and Data) 34

3.5.4 Summary of Performance Constraints . . . 34
3.6 Design Constraints . . . 35
3.6.1 Regulatory and Standards Compliance . . . 35
3.6.2 Hardware and Resource Constraints . . . 35
3.6.3 Software Compatibility . . . 35
3.7 Software System Attributes . . . 35
3.7.1 Reliability . . . 35
3.7.2 Security . . . 36
3.7.3 Maintainability . . . 36
3.7.4 Portability . . . 36

4 Formal Analysis . . . 37
4.1 Verification Approach . . . 37
4.2 Alloy Specification . . . 37
4.2.1 The Model Code . . . 37
4.2.2 Logic and Rationale: What are we proving? . . . 38
4.3 Verification Results . . . 39
4.3.1 Assertion Checking (Solver Metrics) . . . 39
4.3.2 Instance Analysis (Scenario Validation) . . . 39
4.3.3 Conclusion of Analysis . . . 41

5 Generative AI Usage Declaration . . . 42
5.1 Tools Utilized . . . 42
5.2 Usage Description . . . 42
5.2.1 1. Writing Style and Text Refinement . . . 42
5.2.2 Iterative Diagram Design (Draw.io ↔ AI) . . . 42
5.2.3 Formal Model Debugging (Alloy) . . . 42
5.2.4 4. UI Prototyping and Visualization . . . 43
5.3 Verification Statement . . . 43

6 Effort Spent . . . 44

A Requirements Evolution: Version 1.0 to Version 2.0 . . . 45
A.1 Document Revision History . . . 45
A.2 Summary of Changes . . . 45
A.3 Refined Requirements . . . 45
A.3.1 R3: Automated Anomaly Detection (UC4) . . . 45
A.3.2 D.A.3: Vehicle Classification (Speed Range) . . . 46
A.4 Enhanced Requirements . . . 47
A.4.1 R3-ML: Machine Learning Detection Module . . . 47
A.4.2 R4-Enhanced: Community Verification System . . . 47
A.4.3 H3-Enhanced: Inertial Measurement Unit . . . 48
A.5 New Requirements . . . 48
A.5.1 REQ-009: Background Ride Tracking . . . 49
A.5.2 REQ-010: Weather Safety Alerts . . . 49
A.5.3 REQ-011: Water Fountain Locations . . . 49
A.5.4 REQ-012: Cobblestone Avoidance . . . 50
A.6 Signal Processing Specifications (New Section) . . . 50
A.6.1 SP-1: Bandpass Filtering . . . 50
A.6.2 SP-2: Quaternion Orientation Tracking . . . 51
A.7 Performance Requirements Updates . . . 51

A.8 Traceability Matrix Update 52
A.9 Physical Reference Data (New) 52
A.10 Deprecation Notices 52
A.11 Conclusion 52

1 Introduction

1.1 Purpose

The purpose of this document is to present a comprehensive Requirements Analysis and Specification Document (RASD) for the **Best Bike Paths (BBP)** system. This document fully delineates the functional and non-functional requirements, system interfaces, and design constraints imposed on the software.

This specification is intended to serve as the primary reference for the following stakeholders:

- **Development Team**: To understand the specific behaviors, data structures, and algorithms required for implementation.
- **Project Supervisors**: To verify that the proposed solution adheres to the assignment specifications for the, specifically regarding automated data collection and user verification protocols.
- **Testing Team**: To derive test cases and validation scenarios.

1.2 Scope

The **Best Bike Paths (BBP)** application is a software system designed to aggregate crowdsourced data associated to the condition of cycling infrastructure. The system seeks to optimize urban cycling safety and operational efficiency by generating route recommendations prioritized by road quality instead of distance alone.

Consistent with the project requirements, the specific scope includes the implementation of **Automated Data Collection** via smartphone sensors such as Accelerometer and Gyroscope and a rigorous **User Verification Protocol** to ensure data validity.

1.2.1 World Phenomena

These are the entities and events in the physical world that exist independently of the system but influence or are influenced by it.

- **The Cyclist**: The human actor operating the bicycle, whose safety and comfort are the primary objectives.
- **The Bicycle**: The physical vehicle. Its interaction with the road surface generates the vibrations detected by the system.
- **The Road Network**: The physical infrastructure such as streets, bike lanes, paths. Its attributes are asphalt quality, presence of cobblestones, potholes are the core data subject of the system.
- **Weather Conditions**: Meteorological events like Rain, Wind, Snow that affect road safety and route desirability.
- **Physical Obstacles**: Temporary or permanent hazards that present a danger to cyclists.

1.2.2 Shared Phenomena

These are the specific signals and interactions shared between the World and the Machine. They represent the interface through which the system monitors the world and controls its output.

Monitored Phenomena (Inputs)

- **GPS Signals**: The stream of spatiotemporal coordinates ($Latitude, Longitude, Time$) received from the smartphone GPS receiver, representing the Cyclist position and speed.
- **Inertial Sensor Readings**: The raw telemetry data (x, y, z acceleration forces) received from the device accelerometer, representing the physical impact of the Bicycle hitting a road defect.
- **User Inputs**: Manual touches on the screen, such as starting a trip, confirming a detected anomaly, or submitting a manual report.

Controlled Phenomena (Outputs)

- **Map Visualization**: The graphical rendering of the road network, overlaid with color-coded safety scores and specific hazard markers.
- **Route Suggestions**: The calculated path presented to the user, optimized for surface quality.
- **Alerts and Notifications**: Visual or auditory warnings displayed to the user regarding immediate hazards or requests for verification.

1.3 Definitions, Acronyms, and Abbreviations

1.3.1 Definitions

- **Anomaly**: An irregularity in the road surface such as pothole, bump, cracks, broken glass that affects cycling safety.
- **Automated Mode**: A specific operational mode of the application where the smartphone's sensors are active to detect road defects without user intervention.
- **Candidate Anomaly**: A potential road defect detected by the algorithms during a ride. It is stored temporarily and requires user verification before being permanently added to the database.
- **Path Score**: A numerical metric (typically 0-100) representing the quality and safety of a specific Street Segment. A higher score demonstrates a smoother, safer surface.
- **Ride**: A single, continuous bike ride recorded by the app, made up of GPS location points and optional sensor data.
- **Street Segment**: The fundamental unit of the digital map graph. It represents a physical section of a road typically connecting two intersections.
- **Verification**: The mandatory process where a Registered User explicitly confirms or rejects a Candidate Anomaly at the end of a trip to prevent false positive.

1.3.2 Acronyms and Abbreviations

- **API**: Application Programming Interface.
- **BBP**: Best Bike Paths.
- **GDPR**: General Data Protection Regulation (EU Regulation 2016/679).
- **GPS**: Global Positioning System.

- **IMU**: Inertial Measurement Unit. A hardware component in smartphones containing the Accelerometer and Gyroscope used for anomaly detection.
- **RASD**: Requirements Analysis and Specification Document.
- **UI**: User Interface.

1.4 Revision History

Version	Date	Description	Author
1.0	December,2025	First release of the RASD	Shashi, Rajatkant
1.1	January,2026	Updated Version of RASD	Shashi, Rajatkant

Table 1: Document Revision History

1.5 Reference Documents

The following documents were used as primary sources for the requirements and standards described in this specification:

- **Assignment Specification:** *Software Engineering 2 - Project Description (RASD) AY 2025-2026*, Politecnico di Milano.
- **Course Material:** *Software Engineering 2 - Course Slides*, available on the WeBeep Portal.
- **Regulatory Standards:** *Regulation (EU) 2016/679 (GDPR)* regarding data protection.
- **Technical Documentation:** Official developer documentation for Android, iOS, and OpenStreetMap APIs.

For specific URLs and publication details, please refer to the **Bibliography** section at the end of this document.

1.6 Document Structure

This document is organized according to the IEEE 830-1998 standard. The remaining sections are structured as follows:

- **Section 2 (Overall Description)**: Provides a high-level overview of the system context. It defines the product perspective through User Scenarios (Section 2.1.1), the Domain Model (Section 2.1.2), and the State Machine Model (Section 2.1.3). It also categorizes the User Characteristics (Section 2.3) and establishes the Assumptions and Constraints (Section 2.4).
- **Section 3 (Specific Requirements)**: Contains the detailed functional and non-functional requirements. This section serves as the core specification for developers, detailing the User Interfaces (Section 3.1), Functional Requirements via Use Cases and Sequence Diagrams (Section 3.2), and quantitative Performance Requirements (Section 3.3).
- **Section 4 (Formal Analysis)**: Details the formal modeling of critical system components using the Alloy Analyzer to verify the consistency and robustness of the requirements, specifically regarding Data Integrity and GPS handling.
- **Section 5 (Generative AI Usage Declaration)**: Discloses the specific AI tools (e.g., Gemini, ChatGPT) utilized for text refinement, code syntax correction, and diagram logic review, complying with academic integrity guidelines.

- **Section 6 (Effort Spent)**: Details the specific contributions and time allocation of each group member towards the project.

2 Overall Description

2.1 Product Perspective

The Best Bike Paths (BBP) system is a crowdsourced application designed to map the quality of cycling paths. This section describes the context of the system through real-world scenarios, a domain model, and state diagrams.

2.1.1 Scenarios

The following scenarios illustrate how different user personas interact with the BBP system in real-world situations.

Scenario 1: Trip Recording & Manual Reporting

Case 1: Reporting Physical Damage (The Broken Tram Track)

- **Actor:** Raju (Pro Biker)
- **Setting:** Via Valenza, near Porta Genova.
- **Goal:** Report a structural danger on the road.

Raju is on a training ride along the Navigli. He turns onto Via Valenza and suddenly has to brake hard. A section of the old tram tracks has cracked which creates a wide gap in the asphalt that could easily trap a bicycle wheel and cause a crash.

1. Raju stops safely on the sidewalk and hits Pause on the app.
2. He taps Report Issue and selects Manual Insertion.
3. **Location:** Auto-filled as Via Valenza.
4. **Status:** He selects Requires Maintenance.
5. **Details:** He types: Broken tram track pavement - wheel trap hazard.
6. He hits Submit. The system now knows this specific spot is dangerous for thin tires.

Case 2: Reporting a Temporary Hazard (The Broken Glass)

- **Actor:** Shyam (Cautious Commuter)
- **Setting:** Via Vittor Pisani, near Central Station.
- **Goal:** Report a temporary obstacle that causes flat tires.

Shyam is commuting home from work. On the bike lane near Central Station he sees something glittering ahead. He slows down and realizes a crate of green bottles has been dropped which is covering the bike lane in sharp glass shards. This is not a road defect but a temporary danger.

1. Shyam steers around the glass and stops.
2. He opens the report menu and selects Manual Insertion.
3. **Location:** Auto-filled as Via Vittor Pisani.
4. **Status:** He selects Requires Maintenance.

5. **Details:** He types: Large amount of broken glass on cycle path. High puncture risk.
6. He hits Submit. Other users riding blindly into this area will now get a warning.

Case 3: Reporting Poor Infrastructure (The Dark Park)

- **Actor:** Baburao (Casual Rider)
- **Setting:** Parco Sempione near Arco della Pace.
- **Goal:** Report a safety issue related to visibility/lighting.

Baburao is cutting through Parco Sempione at 9:00 PM. Usually, this is a nice route but tonight he notices a long stretch of streetlights is completely broken. It is pitch black which makes him feel unsafe because he cannot see pedestrians or potential attackers.

1. Baburao stops under a working light.
2. He taps Report Issue → Manual Insertion.
3. **Location:** Auto-filled as Parco Sempione Path.
4. **Status:** He selects Sufficient but adds a warning.
5. **Details:** He types: All lights are out. Totally dark and unsafe at night.
6. He hits Submit. The system can now lower the Safety Score of this path during nighttime hours.

Case 4: Reporting Positive Feedback (The New Road)

- **Actor:** Raju (Pro Biker)
- **Setting:** Via Novara, near San Siro Stadium.
- **Goal:** Update the map with a newly paved Perfect road.

Raju is exploring the outer ring of Milan. He turns onto Via Novara which used to be full of holes. To his surprise the city has just finished repaving it. The asphalt is jet black, smooth, and perfect for high-speed riding. The BBP map currently shows it as Grey/Unknown.

1. Raju stops at a red light.
2. He quickly opens the report menu.
3. **Location:** Auto-filled as Via Novara.
4. **Status:** He selects Optimal (The best rating).
5. **Details:** He types: Freshly paved, very smooth, wide lane.
6. He hits Submit. This positive report raises the score of the road and the routing algorithm will now suggest this path to users like Shyam who want a smooth ride.

Scenario 2: Path Visualization & Routing

Case 1: Prioritizing Surface Quality (The Safe Commute)

- **Actor:** Shyam (Registered User)
- **Setting:** Morning commute, Città Studi to Piazza Gae Aulenti.
- **Goal:** Avoid Milan's dangerous cobblestones (pavé) and traffic.

Shyam drinks his espresso and opens BBP to plan his ride to work. He wants to avoid the rough cobblestones that make his hands numb.

1. **Input:** Origin: Via Pacini. Destination: UniCredit Tower.
2. **Visualization:** The system displays two options:
    - **Path A (Grey - 15 mins):** Direct route via Corso Buenos Aires. It is short but the line is dotted with yellow warnings. Tooltip: *Status: Heavy Traffic / Construction Work.* Score: 55/100.
    - **Path B (Green - 19 mins):** A longer route weaving through Porta Venezia Gardens. The line glows green. Tooltip: *Status: Optimal. Surface: Smooth Asphalt.* Score: 94/100.
3. **Decision:** Shyam values his comfort over 4 minutes. He taps Path B and hits Start Navigation. He enjoys a stress-free ride through the park avoiding the chaos of the main boulevard.

Case 2: Adapting to Weather (The Mud Avoidance)

- **Actor:** Shyam (Registered User)
- **Setting:** A rainy November morning.
- **Goal:** Reach the office without getting stuck in mud.

It is pouring rain in Milan. Shyam needs to get to a client meeting near Navigli. Usually, his favorite route cuts through a gravel path along the canal bank because it is scenic and car-free.

1. **Input:** Origin: Porta Genova. Destination: Assago Forum.
2. **System Logic:** The system checks the External Weather Service. It sees Heavy Rain. It automatically applies a penalty to unpaved surfaces (gravel/dirt) because they will be muddy and slippery.
3. **Visualization:**
    - The usual canal path is now marked Red. Tooltip: *Warning: Likely Muddy/Slippery due to rain.*
    - The system suggests a new Blue Route that sticks to the paved main road running parallel to the canal.
4. **Decision:** Shyam sees the warning. He realizes the gravel path would be a mess. He accepts the paved detour, arriving at his meeting dry and safe.

Case 3: Real-Time Detour (The Accident Avoidance)

- **Actor:** Shyam (Registered User)
- **Setting:** Mid-ride on Via Torino.
- **Goal:** Avoid getting stuck behind a blockage.

Shyam is happily following his green route along Via Torino. Suddenly, his phone buzzes on the handlebar mount.

1. **Event:** Two blocks ahead, another user (Raju) has just reported a Tram Breakdown blocking the entire lane.
2. **System Action:** The BBP server receives Raju's report. It instantly recalculates scores for the affected segment. The score drops to 10/100 (Blocked).
3. **Visualization:** The map screen flashes: *New Hazard Detected Ahead: Blocked Lane.*
4. **Re-routing:** The blue navigation line snaps to a new shape. It guides Shyam to turn right onto a side street immediately, bypassing the blockage completely.
5. **Outcome:** Shyam pedals past the traffic jam on the parallel street where he sees the stuck tram and angry drivers, thankful he was diverted in time.

Case 4: Time-Dependent Safety (The Night Mode Route)

- **Actor:** Shyam (Registered User)
- **Setting:** Leaving the office late (10:30 PM).
- **Goal:** Get home safely using well-lit streets.

Shyam has worked late. His usual morning route goes through Parco Sempione which is lovely during the day. However, he knows it can be dark and isolated at night.

1. **Input:** Origin: Cadorna Office. Destination: Arco della Pace.
2. **System Logic:** The system checks the time (22:30). It accesses the Safety Profile of the park. Since Baburao previously reported Broken Lights in the park, the system applies a heavy Darkness Penalty to that path after sunset.
3. **Visualization:**
    - The direct path through the park is now Greyed Out. Tooltip: *Low Visibility / Poor Lighting Reported.*
    - The recommended Green Path loops around the outside of the park sticking to the well-lit main ring road.
4. **Decision:** Shyam appreciates the suggestion. He feels much safer riding under the streetlights of the main road than risking the pitch-black park path.

Scenario 3: Automated Reporting

Case 1: The True Positive (The Cobblestone Trap)

- **Actor:** Baburao (Registered User - Passive Mode)
- **Setting:** Via Paolo Sarpi (Chinatown).
- **Goal:** Ride to the market without distraction.

Baburao is riding his heavy city bike to buy vegetables. He toggles Automated Mode and puts the phone in his jacket pocket. He turns onto Via Paolo Sarpi a pedestrian-friendly street paved with uneven cobblestones.

1. **Event:** Baburao hits a sunken stone block that has collapsed slightly causing a violent jolt.
2. **Sensor Logic:**
    - **Speed:** 19 km/h (Confirmed Biking).
    - **Accelerometer:** Z-axis spike of 2.6G (High Impact).
    - **Action:** The system flags this GPS point [45.48, 9.17] as a `Candidate_Anomaly`.
3. **Verification:** At the end of the ride, the app asks: *We detected a bump near Chinatown. Was this a road defect?*
4. **Outcome:** Baburao remembers the jar to his spine. He taps Confirm. The system records a verified hazard lowering the score of that street segment.

Case 2: The False Positive (The Curb Jump)

- **Actor:** Baburao (Registered User - Passive Mode)
- **Setting:** Piazza del Duomo.
- **Goal:** Parking the bike to visit a friend.

Baburao finishes his ride near the Duomo. To get to the bike racks he steers off the road and intentionally hops his bike up a high curb onto the sidewalk.

1. **Event:** The bike lands hard on the sidewalk pavement.
2. **Sensor Logic:**
    - **Speed:** 12 km/h (Still in biking range).
    - **Accelerometer:** Z-axis spike of 3.1G (Massive shock).
    - **Action:** The system flags this as a `Candidate_Anomaly`, assuming it might be a massive crater in the road.
3. **Verification:** When stopping the mode, the app asks: *Severe shock detected near Piazza del Duomo. Pothole?*
4. **Outcome:** Baburao realizes that was just him jumping the curb. He taps Reject / Ignore. The data is discarded, preventing false information from marking the Piazza as damaged.

Case 3: The Non-Pothole Obstacle (The Metal Plate)

- **Actor:** Baburao (Registered User - Passive Mode)
- **Setting:** Porta Romana (Construction Zone).
- **Goal:** Riding through ongoing roadworks.

Baburao is navigating the traffic near Porta Romana where the tram lines are being repaired. The construction crew has placed large steel plates over the road to cover holes.

1. **Event:** Baburao rides over the steel plate. It isn't a hole but the 2-inch height difference causes a sharp loud CLANG and a significant vibration.
2. **Sensor Logic:**
    - **Speed:** 22 km/h.
    - **Sensors:** Detect a sharp vertical rise followed immediately by a drop.

- **Action:** System flags a `Candidate_Anomaly`.

3. **Verification:** The app shows the pin location. Baburao knows it wasn't a pothole, but it is an annoying obstacle.
4. **Outcome:** He taps Confirm. In the optional comment box (if he wants), he could select Roadwork, but even a simple confirmation helps BBP warn users like Raju (on his road bike) that this surface is not smooth.

Case 4: The Handling Error (The Pocket Fumble)

- **Actor:** Baburao (Registered User - Passive Mode)
- **Setting:** Stopping for Gelato near Castello Sforzesco.
- **Goal:** Taking a break.

Baburao decides to stop for a gelato. He is still rolling slowly toward the bench. He tries to pull his phone out of his pocket while still moving to check the time, but he fumbles it.

1. **Event:** The phone slips from his hand which bounces off his knee and he catches it before it hits the handlebar.
2. **Sensor Logic:**
   - **Speed:** 6 km/h (Borderline biking speed).
   - **Gyroscope:** Wild tumbling rotation.
   - **Accelerometer:** Erratic spikes in all directions.
   - **Action:** The system is confused. It flags a `Candidate_Anomaly` because the movement was violent.
3. **Verification:** The app asks: *Anomaly detected near Castello. Confirm?*
4. **Outcome:** Baburao laughs at his own clumsiness. He taps Reject / Not a Road Issue. This ensures the map stays accurate and doesn't blame the road for Baburao's slippery fingers.

2.1.2 Domain Class Diagram

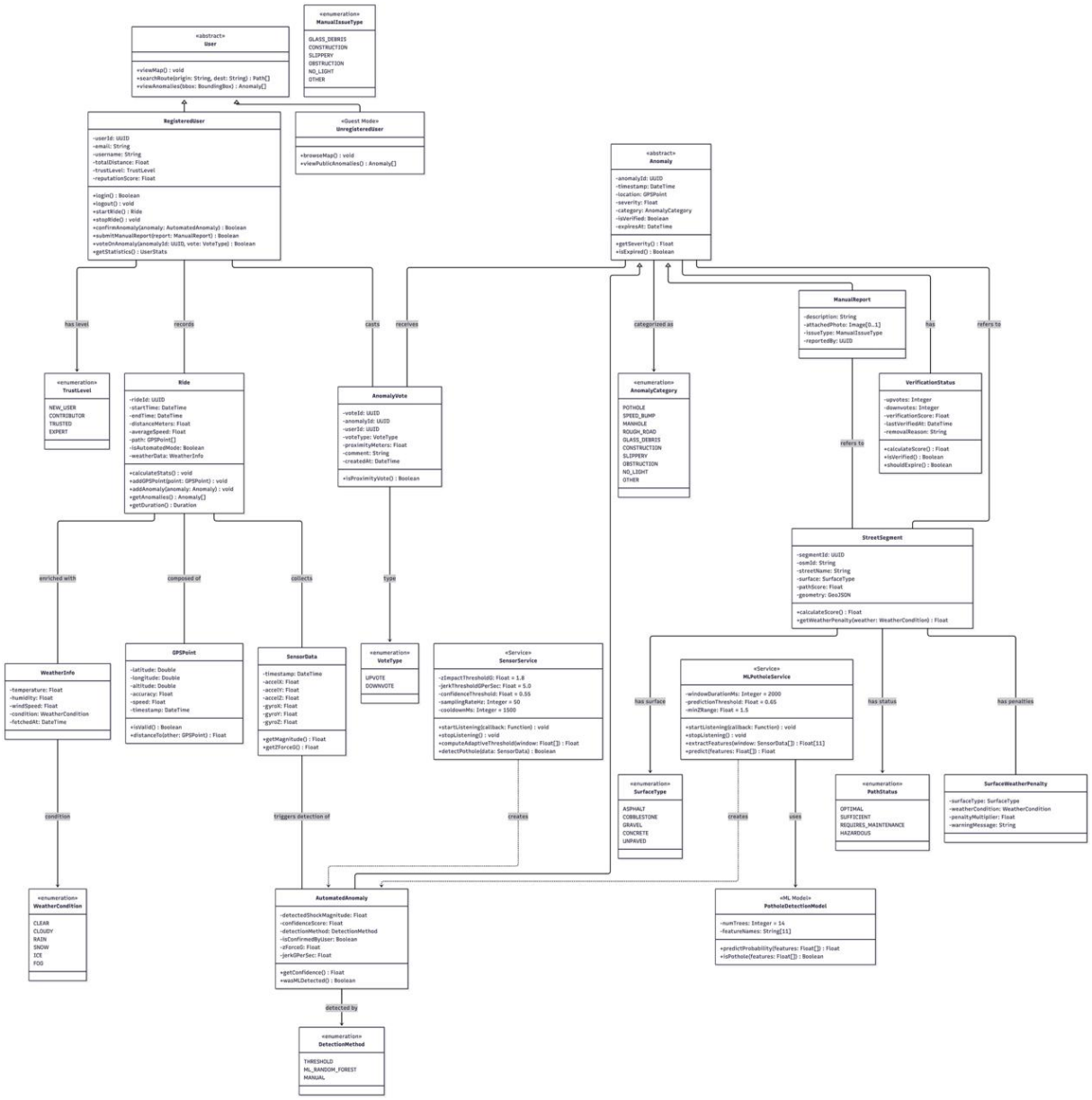

Figure 1: Domain Class Diagram for the Best Bike Paths (BBP) System.

Description of Entities: The Domain Model represents the core entities involved in the BBP system and their relationships. The model is designed to support both manual and automated data collection, as well as the path visualization requirements.

1. **User Hierarchy**

   - `User (Abstract)`: Represents the generic user of the system. It encompasses the shared capabilities available to all actors, such as viewing the map and searching for routes (`searchRoute`, `viewMap`). This design allows unauthenticated users (Guests) to access visualization features without requiring an account.
   - `RegisteredUser`: Represents a cyclist who has created an account. This entity manages personal data (`email`, `username`) and is responsible for active contributions to the system, such as recording `Rides` and submitting `Reports`.

- `UnregisteredUser`: Represents a guest user. They inherit the visualization capabilities from the parent `User` class but do not have persistent data or the ability to contribute information.

2. **Ride and Sensor Data (Automated Mode)**
   - `Ride`: Represents a single cycling session recorded by a `RegisteredUser`. It acts as an aggregate root for the data collected during the trip.
   - `GPSPoint`: Represents the spatiotemporal data (latitude, longitude, timestamp) that forms the path of the ride.
   - `SensorData`: This entity captures raw telemetry from the mobile device accelerometer and gyroscope. It is associated with a `Ride` only when the user enables Automated Mode. This data is processed to detect anomalies (shocks) indicative of road defects.
   - `WeatherInfo`: Represents meteorological data (temperature, wind, condition) fetched from an external service to enrich the ride context.
3. **Reporting System**
   - `Report (Abstract)`: Generalizes the concept of feedback on road conditions. It provides a unified interface for the system to process both user generated and machine generated issues.
   - `ManualReport`: Represents an issue explicitly entered by a user. It includes a description a category (via `ObstacleType`) and an optional photo.
   - `AutomatedAnomaly`: Represents a potential hazard detected by the sensor algorithm. Crucially it includes an `isConfirmedByUser` flag enforcing the requirement that users must verify automated findings to prevent false positives.
4. **Map and Routing**
   - `StreetSegment`: Represents a physical section of the road network. It holds a dynamic `currentScore` attribute, which is updated based on the valid `Reports` associated with that segment. This score is utilized by the routing algorithm to calculate the Best Path.
   - `PathStatus`: An enumeration defining the quality of a segment (OPTIMAL, SUFFICIENT, REQUIRES_MAINTENANCE, HAZARDOUS).

Key Relationships

- **Data Acquisition**: A `RegisteredUser` records `0..*` `Rides`. Each `Ride` is composed of `1..*` `GPSPoints` and may collect `0..*` `SensorData` packets.
- **Anomaly Detection**: `SensorData` triggers the creation of an `AutomatedAnomaly`. This relationship highlights the dependency between raw hardware inputs and the system logic for identifying road defects.
- **Scoring Logic**: All `Reports` refer to a specific `StreetSegment`. The aggregation of these reports determines the segment's `PathStatus` and `currentScore`.

2.1.3 State Machine Diagram

To clarify the dynamic behavior of the application during a cycling session, Figure 2 illustrates the lifecycle of a `Ride` entity. This diagram specifically highlights how the system manages sensor resources and data validation.

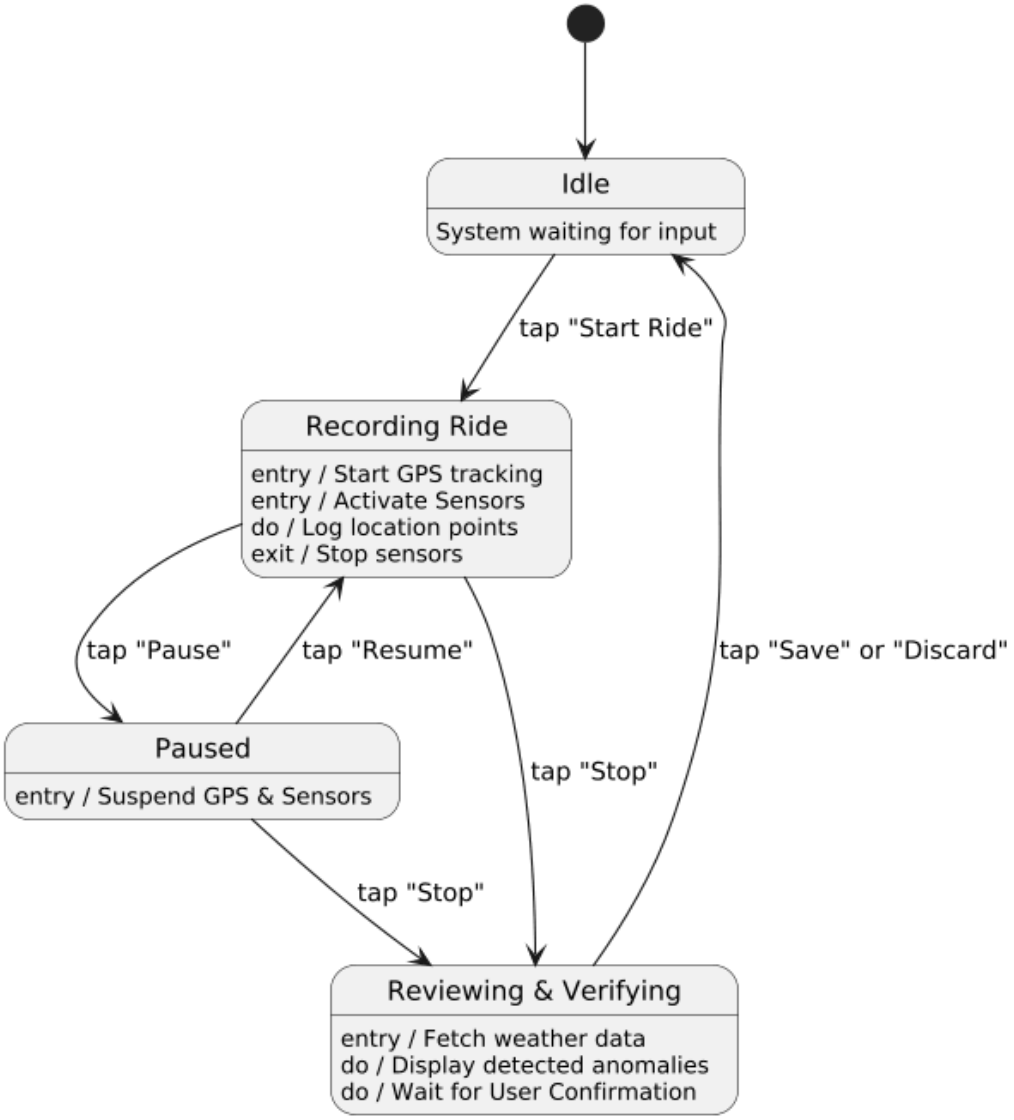

Figure 2: State Machine Diagram showing the lifecycle of a Ride session.

Description of States The lifecycle consists of four primary states that ensure data integrity and battery efficiency:

1. **Idle**
   - The application is initialized and awaiting user input.
   - Location services may be active for map visualization, but no persistent data is being recorded.
2. **Recording Ride**
   - **GPS Logging:** The system actively records `GPSPoints` to reconstruct the route.
   - **Sensor Activation:** If Automated Mode is enabled, the system activates the Inertial Measurement Unit (Accelerometer/Gyroscope). It continuously buffers sensor data to detect high-frequency shocks indicative of road defects.
   - **Anomaly Flagging:** When a shock threshold is exceeded, the system flags the current location as a `Candidate_Anomaly` in temporary storage.

3. **Paused**
    - Entered when the user temporarily halts the ride.
    - **Resource Conservation:** GPS logging frequency is reduced or suspended.
    - **Noise Filtering:** Crucially **sensor data collection is completely suspended**. This prevents false positives caused by non-cycling movements from being recorded as road defects.
4. **Reviewing & Verifying**
    - This transition state occurs immediately after the user stops the ride but before data persistence.
    - **Data Enrichment:** The system fetches weather metadata for the ride duration.
    - **User Confirmation Loop:** The system presents a summary of all `Candidate_Anomalies` detected during the recording phase. The user must explicitly **confirm** or **reject** these findings. This step is mandatory to ensure that only verified hazards impact the global Path Score.

Transitions

- **Start Ride:** Transitions the system from Idle to Active recording.
- **Stop:** Triggers the verification process. Note that Stop is available from both Recording and Paused states.
- **Save / Discard:** The final action in the Review state. **Save** commits the confirmed anomalies and track data to the database; **Discard** wipes the temporary session data.

2.1.4 System Interfaces

The BBP system interacts with external entities to function:

- **Hardware**: Interfaces with the smartphone**GPS Receiver**, **Accelerometer**, and **Gyroscope**.
- **Software**: Uses external **Map APIs** for visualization and **Weather APIs** for trip enrichment.

2.2 Product Functions

The Best Bike Paths (BBP) system provides a comprehensive set of features designed to crowdsource road quality data and assist cyclists in finding the safest and most efficient routes. The functions are categorized by the primary actors who utilize them.

2.2.1 User Account Management

- **Registration**: Allows new users to create a personal account, becoming Registered Users. This enables them to contribute data and track their history.
- **Login/Logout**: Secure authentication for Registered Users to access personalized features.
- **Profile Management**: Users can manage their personal details and preferences.

2.2.2 Trip Management (Registered Users Only)

- **Trip Recording**: The system allows users (like Raju) to start, pause, and stop the recording of a cycling session. During the ride the system tracks the GPS location to reconstruct the path.
- **Statistics Calculation**: Upon completion of a trip the system calculates and displays performance metrics including Total Distance, Average Speed, Elevation Gain, and Duration.
- **Weather Enrichment**: The system automatically queries an external weather service to retrieve meteorological data (Temperature, Wind Speed, Weather Conditions) for the specific time and location of the trip, saving this context with the ride history.
- **Trip History**: Users can browse a log of their past trips such as viewing the map traces and associated statistics.

2.2.3 Data Acquisition & Reporting

BBP utilizes crowdsourcing to build its map of road conditions. This occurs in two distinct modes:

A. Manual Reporting Mode

- **Issue Reporting**: Registered users can manually insert information about a specific street segment. This includes tagging the Status and identifying specific Obstacles.
- **Geotagging**: The system automatically associates the report with the user current GPS location or a location selected on the map.

B. Automated Reporting Mode

- **Smart Activity Recognition**: The system monitors GPS speed to infer if the user is currently biking. It automatically activates sensors when the speed is within a biking range and disables them when walking or driving to prevent false data.
- **Sensor Fusion & Anomaly Detection**: When active, the system reads data from the device Accelerometer and Gyroscope. It analyzes this stream to detect significant vertical shocks or anomalous movements indicative of road defects.
- **User Confirmation Protocol**: To filter out false positives like phone drops or curb jumps, the system stores detected anomalies locally. At the end of the ride it presents a summary to the user requiring explicit confirmation or rejection of the detected hazards before uploading them to the server.

2.2.4 Visualization & Routing

These functions are available to both Registered and Unregistered Users.

- **Path Search**: Users can input an Origin and Destination to request a route.
- **Route Calculation**: The system computes possible paths using a weighted algorithm. The Cost of a path is determined not just by distance but by its Path Score which penalizes segments with poor status.
- **Map Visualization**: The system displays the calculated routes on an interactive map. Paths are color-coded or highlighted based on their score display as Green for Optimal, Red for Bad, allowing users to visually assess the safety of the route before riding.
- **Segment Inspection**: Users can tap on specific road segments on the map to view detailed information, such as the current status, recent reports, and specific obstacles tagged by the community.

2.2.5 Data Processing (Server Side)

- **Score Updating**: The system continuously updates the `CurrentScore` of street segments as new reports (Manual or Confirmed Automated) are received.
- **Persistence**: All valid trips, reports, and user data are securely stored in the system database.

2.3 User Characteristics

The Best Bike Paths system is designed for a diverse demographic of cyclists, ranging from casual city commuters to professional athletes, as well as tourists. The user base is categorized into two primary groups based on their level of interaction with the system: Registered Users (who contribute data) and Unregistered Users (who consume data).

2.3.1 Registered Users

This group represents the core contributors to the BBP ecosystem. They are typically regular cyclists who own a smartphone and have a basic to intermediate level of technical proficiency (familiar with GPS apps and account management). Within this group, we identify three distinct profiles with unique motivations:

A. The Safety First Commuter (e.g Shyam)

- **Profile**: Daily cyclists commuting to work or school such as students, office workers. They ride city bikes or e-bikes.
- **Goals**: Their primary goal is **Safety** and **Comfort**. They want to avoid potholes, cobblestones (pavé), and dangerous traffic, even if the route is slightly longer.
- **Interaction**: They heavily rely on the Routing feature to find the greenest path. They occasionally submit **Manual Reports** for immediate hazards such as broken glass, blocked lanes to help the community.

B. The Performance Athlete (e.g.Raju)

- **Profile**: Sports enthusiasts who ride road bikes or mountain bikes for training. They are interested in data and statistics.
- **Goals**: Their primary goal is **Performance Tracking**. They use the app to log distance, speed, and elevation gain. They seek smooth, uninterrupted roads (high "Score") to maintain speed and avoid damage to expensive equipment.
- **Interaction**: They use the **Trip Recording** feature for every ride. They are diligent about **Manual Reporting** of infrastructure defects like cracks, dangerous tram tracks that affect high speed riding.

C. The Passive Contributor (e.g. Baburao)

- **Profile**: Casual riders who may not be tech-savvy or interested in typing reports while riding. They want a "set it and forget it" experience.
- **Goals**: To ride without distraction while contributing to the ecosystem.
- **Interaction**: They primarily use the **Automated Mode**. They enable the sensors at the start of the ride and put the phone in their pocket. Their interaction is limited to the **Post-Ride Confirmation** screen where they quickly verify detected anomalies.

2.3.2 Unregistered Users (Guests)

This group consists of occasional users who do not wish to create an account or share personal data.

The Tourist / Occasional Rider (e.g., Tom)

- **Profile**: Tourists visiting the city, users of bike sharing services or citizens who ride very rarely.
- **Goals**: To get from Point A to Point B quickly and safely without the friction of a signup process.
- **Technical Proficiency**: Varies but the interface for them must be immediate and intuitive.
- **Interaction**: They strictly use the **Visualization** and **Path Finding** features. They cannot record trips or report issues. They act strictly as **Data Consumers**, benefiting entirely from the crowd-sourced data collected by Registered Users.

2.3.3 Usage Environment

- **Mobile Usage**: The majority of interactions (Recording, Reporting, Navigation) occur outdoors, often in bright sunlight, rain, or while wearing gloves. The UI for these users is designed for high visibility and quick interactions to ensure safety while riding.
- **Desktop/Tablet Usage**: Detailed route planning and viewing of trip history (for Registered Users) may occur indoors on larger screens.

2.4 Assumptions, Dependencies, and Constraints

2.4.1 Assumptions

Assumptions are factors that are believed to be true during the design process. If these change, the system logic may need to be revisited.

- **D.A.1 - Device Placement (Automated Mode)**: It is assumed that during Automated Mode, the smartphone is either securely mounted to the bicycle handlebar or placed in a pocket/bag relatively close to the rider body. This ensures that road vibrations are transmitted to the device accelerometer with sufficient fidelity to distinguish a pothole from random noise.
- **D.A.2 - User Honesty**: It is assumed that Registered Users generally act in good faith when confirming or rejecting detected anomalies. While the system aggregates data to filter outliers it relies on a wisdom of the crowd assumption that the majority of user verifications are truthful.
- **D.A.3 - Vehicle Classification**: The system assumes that a sustained speed between 5 km/h and 35 km/h correlates with cycling. Speeds consistently exceeding this range are assumed to be a motor vehicle, and speeds below this are assumed to be walking, triggering the Context Filter to pause sensor collection.
- **D.A.4 - GPS Accuracy**: It is assumed that the mobile device provides GPS coordinates with a reasonable margin of error (approx. 5-10 meters) to correctly map a user to a specific `StreetSegment`.

2.4.2 Dependencies

The BBP system relies on external systems and interfaces that are outside the control of the development team.

- **D.D.1 - Global Positioning System (GPS)**: The core functionality (Tracking, Routing, Geotagging) is entirely dependent on the availability and accuracy of satellite GPS signals. Functionality may be degraded in urban canyons known as narrow streets with tall buildings or tunnels.
- **D.D.2 - External Map Provider**: The system depends on a third-party mapping service (e.g., OpenStreetMap, Google Maps Platform) to provide the underlying city graph, street names, and rendering tiles.
- **D.D.3 - Meteorological Service**: The "Trip Enrichment" feature depends on an external Weather API (e.g., OpenWeatherMap) to provide real-time temperature and wind data based on the ride's timestamps.
- **D.D.4 - Mobile Operating System**: The application depends on the Android/iOS APIs to grant access to hardware sensors (Accelerometer, Gyroscope) and background location services.

2.4.3 Constraints

Constraints are limitations imposed on the design by hardware, regulations, or business requirements.

- **D.C.1 - Connectivity Requirements**: While trip recording and sensor detection can function offline (local storage), the system requires an active Internet connection (4G/5G/Wi-Fi) to:
  - Login/Authenticate.
  - Calculate and visualize routes (Server-side logic).
  - Upload confirmed reports to the community map.
- **D.C.2 - Battery Consumption**: The Automated Mode algorithm must be optimized to sample sensor data at a frequency (e.g., 50Hz) that balances detection accuracy with battery drain. The application cannot consume more than 15% of battery per hour of riding to remain viable for users.
- **D.C.3 - GDPR & Privacy**: The system must comply with data protection regulations (GDPR).
  - Exact ride traces must be private to the user by default.
  - Data aggregated for the public map (potholes, scores) must be anonymized, stripping any link to the specific user who reported it.
- **D.C.4 - Safety & Distraction**: The User Interface (UI) must be designed to minimize distraction. Complex interactions like typing a manual report description are constrained to be performed only when the user is stationary (speed = 0) or after the ride is finished.

3 Specific Requirements

3.1 User Interfaces

The User Interface (UI) of the BBP application is designed with a specific focus on safety, battery efficiency, and data integrity. Since the primary user is a cyclist often in motion or stopping briefly outdoors, the visual language prioritizes:

- **Dark Mode Aesthetic:** To reduce glare in low-light conditions and minimize battery consumption on OLED screens during long rides.
- **High Contrast Accents:** Key actions use a distinct "Neon Green" (#00E676) to ensure visibility in bright sunlight.
- **Large Touch Targets:** Buttons and interactive elements are oversized to facilitate interaction while wearing cycling gloves.

The following mockups illustrate the four critical interaction flows.

3.1.1 Onboarding and Main Dashboard

Figure 4 illustrates the entry points for the user.

- **Registration (Left):** A clean, minimalist login screen that offers a "Guest Mode" to lower the barrier to entry for tourists or casual users.
- **Dashboard (Right):** The hub of the application. It features a massive "START RIDE" button that serves as the primary call-to-action ensuring users can begin tracking instantly. The Automated Sensor Mode toggle is prominently displayed giving users clear control over their privacy and battery usage.

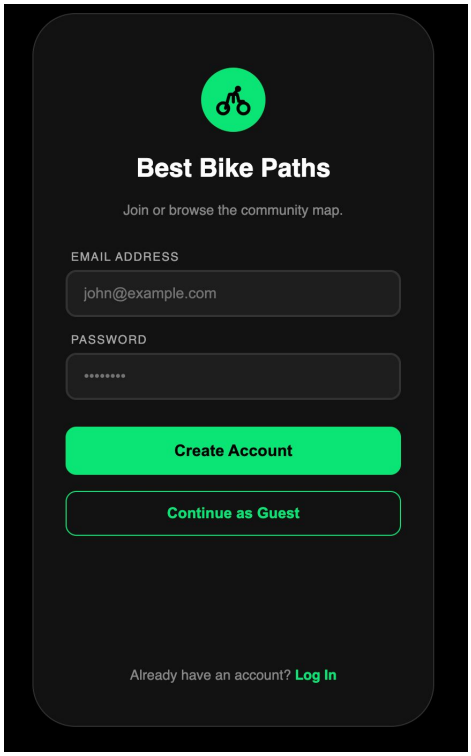

Figure 3: Login & Registration Screen.

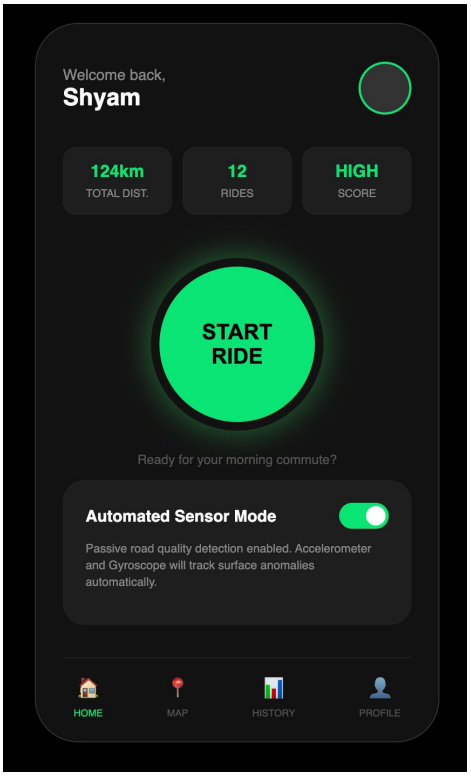

Figure 4: User Dashboard with Sensor Toggle.

3.1.2 Reporting and Verification

Figure 5 demonstrates the data collection interfaces.

- **Manual Reporting (Left):** Accessed during a stop this screen uses a grid of large distinct icons (e.g., Pothole, Glass, No Light). This layout minimizes cognitive load, allowing users to quickly categorize a hazard without typing.
- **Post-Ride Verification (Right):** The Ride Summary screen appears immediately after stopping. It presents a list of anomalies detected by the automated sensors. The user must explicitly "Confirm" (Green Check) or "Reject" (Red X) each item. This "Human-in-the-loop" verification is the primary mechanism for preventing false positives (e.g., phone drops) from polluting the database.

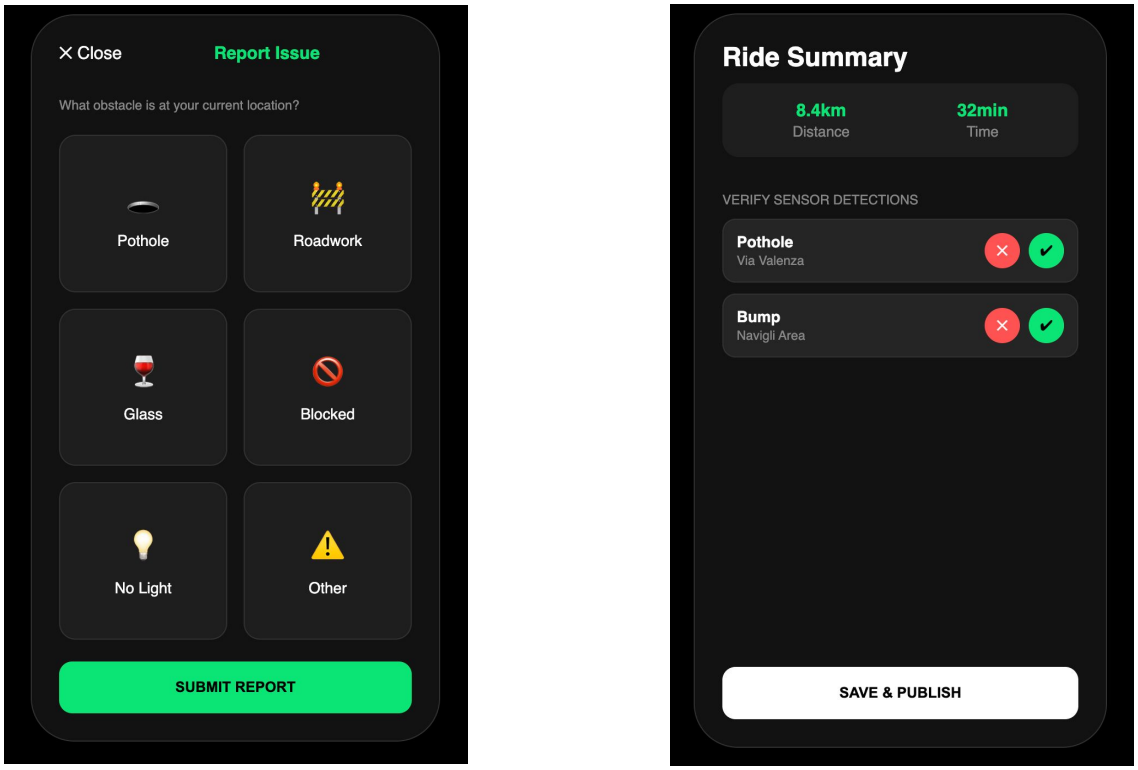

Figure 5: Data Collection Interfaces: Manual Reporting (left) and Post-Ride Verification (right).

3.2 Hardware Interfaces

The BBP application is designed to run on standard commercial smartphones. The software interacts with the following hardware components via the operating system's abstraction layer.

H1: Smartphone Device The application requires a smartphone capable of supporting Android (version 10.0+) or iOS (version 14.0+). The device must possess a capacitive touch screen for the user interactions described in Section 3.1.

H2: Global Positioning System (GPS) Receiver The software requires access to the device's GPS receiver to track the user's geolocation.

- **Input:** The application reads a stream of geolocation data (Latitude, Longitude, Altitude, Accuracy) at a frequency of 1 Hz.

- **Constraint:** The hardware must provide a horizontal accuracy of at least 10 meters to correctly map anomalies to specific street segments.

H3: Inertial Measurement Unit (IMU) / Accelerometer *Critical for Automated Anomaly Detection.* The software interfaces with the device's internal 3-axis accelerometer to detect road irregularities.

- **Input:** The application captures raw acceleration data (m/s^2) on the x, y, and z axes.
- **Frequency:** The hardware must support a sampling rate of at least 50 Hz (50 samples per second) to ensure that brief impacts e.g. hitting a pothole at speed are not missed between sampling intervals.
- **Data Flow:** The sensor readings are buffered in the device volatile memory (RAM) during the ride and processed locally by the application detection algorithm.

H4: Network Interface The application requires a cellular (4G/5G) or Wi-Fi radio interface to communicate with the central backend server for user authentication and the uploading of verified ride data.

3.3 Software Interfaces

The BBP system relies on specific external software APIs and operating system libraries to function.

S1: Mobile Operating Systems The client application interacts with the native OS to access hardware sensors (Accelerometer) and background services.

- **Android:** The application uses the Android Sensor Framework (part of the Android SDK) to retrieve `SensorEvent` data [4].
- **iOS:** The application uses the Core Motion framework to access accelerometer data [1].

S2: Map and Geolocation Service To display routes and visual markers, the application interfaces with an external map provider.

- **Interface:** OpenStreetMap (OSM) API [7] or Google Maps SDK [5].
- **Purpose:** The system sends coordinate data (Latitude, Longitude) to this interface and receives map tiles and routing geometry in return.
- **Data Format:** Communication is handled via RESTful HTTP requests returning JSON or Protocol Buffer data.

S3: Meteorological Service To warn users of weather conditions that might affect road safety (e.g., ice, rain), the system queries an external weather provider.

- **Interface:** OpenWeatherMap API [8].
- **Purpose:** The system sends the user's current location to the API and receives current weather conditions (Precipitation, Temperature, Wind Speed).

S4: Data Base Management System (DBMS) The backend system interacts with a relational database e.g., PostgreSQL or MySQL to persistently store user profiles, ride sessions, and verified anomaly data.

3.4 Functional Requirements

3.4.1 Data Requirements & Classification

To ensure database consistency, the system classifies road issues into two distinct categories:

A. Automated Detection (Inertial Types) Detected by the accelerometer ($> 2.0g$).

- `POTHOLE`: Sharp depression $>$ 3cm.
- `SPEED_BUMP`: Intentional traffic calming.
- `MANHOLE`: Sunken utility cover.
- `ROUGH_ROAD`: Sustained vibration (cobblestones).

B. Manual Reporting Options Reported by user input for visual hazards.

- `GLASS_DEBRIS`: Broken bottles, sand, gravel.
- `CONSTRUCTION`: Road work barriers.
- `SLIPPERY`: Ice, oil, wet leaves.
- `OBSTRUCTION`: Parked cars, fallen trees.
- `OTHER`: Text description required.

3.4.2 Use Case Diagram

Figure 6 depicts the system boundary and primary actors for the BBP application.

The diagram highlights the specific responsibilities of the "Automated Data Collection" module:

- **Sensor Management:** The "Cyclist" (Primary Actor) can interact with the "Toggle Sensor Mode" use case to manually enable or disable data collection.
- **Verification Logic:** The "Stop Ride" use case includes the "Verify Anomalies" process. This dependency (shown by the «`include`» relationship) enforces that data validation is a mandatory step before a ride session can be successfully closed.
- **External Dependencies:** The system relies on the "Weather API" and "Map Service" (Secondary Actors) to provide contextual data during the "Start Ride" and "View Risk Map" processes.

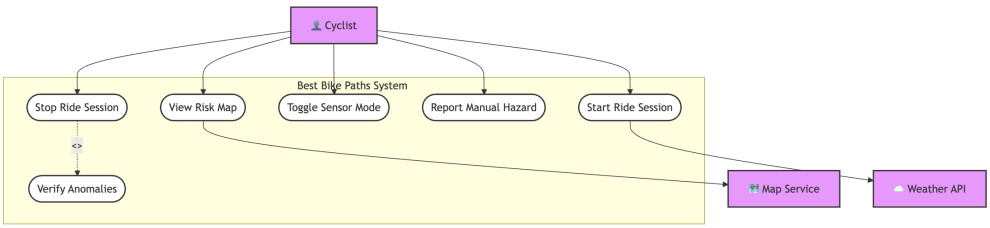

Figure 6: Use Case Diagram showing the User interactions and Verification flow.

3.4.3 Detailed Use Cases

This section provides a comprehensive breakdown of the functional requirements through tabular Use Case specifications. It covers user-initiated actions, automated system processes, and exception handling.

Use Case ID	**UC1: User Registration and Login**
Actors	Cyclist, Backend Server
Goal	To identify the user and associate ride data with a persistent profile.
Preconditions	The user has installed the application and has internet connectivity.
Main Flow	1. User opens the app and selects "Sign Up" or "Login". 2. User enters valid credentials (Email/Password). 3. System validates credentials against the Backend Server. 4. System retrieves the user's settings (e.g., preferred map layers). 5. System displays the Dashboard.
Alternative Flows	*A1: Password Reset.* User clicks "Forgot Password," triggers email recovery flow. *A2: Guest Mode.* User selects "Ride without Account." Data is stored locally only.

Table 2: Use Case: User Registration and Login

Use Case ID	**UC2: Start Ride Session**
Actors	Cyclist, GPS Receiver, Weather API
Goal	To initialize tracking and contextual data recording.
Preconditions	User is logged in; Location Services are enabled on the OS.
Main Flow	1. User taps the "Start Ride" button. 2. System requests current GPS accuracy. 3. **System Check:** If horizontal accuracy $< 10m$, proceed. 4. System calls **Weather API** to fetch current conditions (Rain, Wind). 5. System starts the ride timer and enables the "Stop" button.
Exceptions	*E1: GPS Weak.* If accuracy $> 10m$, System shows a warning: "Waiting for better GPS signal..."

Table 3: Use Case: Start Ride Session

Use Case ID	**UC3: Toggle Automated Sensors**
Actors	Cyclist, Accelerometer (Hardware)
Goal	To allow the user to opt-in/out of passive data collection during a ride.
Preconditions	A ride session is active.
Main Flow	1. User views the "Automated Sensor Mode" toggle on the ride screen. 2. User taps the toggle to **ON**. 3. System registers a listener for the Accelerometer sensor at 50Hz. 4. System buffers the raw z-axis data in RAM. 5. User taps the toggle to **OFF**. 6. System unregisters the sensor listener to conserve battery.
Postconditions	Visual indicator (Green/Grey) reflects the recording status.

Table 4: Use Case: Toggle Automated Sensors

Use Case ID	**UC4: Automated Anomaly Detection**
Actors	System (Internal Process)
Goal	To filter raw sensor data into potential candidate anomalies.
Trigger	Continuous loop while "Automated Sensor Mode" is ON.
Logic Flow	1. System reads a 1-second buffer of accelerometer data. 2. System calculates the vertical force vector (G_z). 3. **Threshold Check:** If $G_z > 2.0g$ (Severe Bump): a. Capture the timestamp and GPS coordinate. b. Flag as "Candidate Anomaly (Type: Bump)". c. Store in temporary "Verification Queue". 4. System discards non-peak data to free memory.

Table 5: Use Case: Automated Anomaly Detection (System Internal)

Use Case ID	**UC5: Stop Ride & Verify**
Actors	Cyclist, Local Database
Goal	To finalize the ride and manually filter false positives.
Preconditions	Ride is active; Verification Queue contains items.
Main Flow	1. User taps "STOP RIDE". 2. System halts all sensors. 3. System presents the "Ride Summary" screen with the list of Candidate Anomalies. 4. **Verification Loop:** - User reviews "Anomaly #1 (Time: 12:05)". - User selects "Confirm" (It was a pothole) or "Reject" (I jumped a curb). 5. User taps "Save Ride". 6. System commits only "Confirmed" anomalies to the Local Database.
Exceptions	*E1: No Anomalies.* If the queue is empty, the Verification screen is skipped, and the ride is saved immediately.

Table 6: Use Case: Stop Ride and Verification

Use Case ID	**UC6: Data Synchronization**
Actors	System, Backend Server
Goal	To transmit verified data to the central server.
Trigger	Immediately after UC5 (Save Ride).
Main Flow	1. System checks for internet connectivity. 2. System serializes the Ride Object (Path + Verified Anomalies) to JSON. 3. System sends HTTP POST request to `/api/v1/rides`. 4. Server returns `200 OK`. 5. System marks the local record as "Synced".
Exceptions	*E1: Offline.* If no internet is available, System marks record as "Pending Upload". A background job retries when connectivity is restored.

Table 7: Use Case: Data Synchronization

Use Case ID	**UC7: View Risk Map**
Actors	Cyclist, Map Service
Goal	To visualize safe and unsafe paths.
Main Flow	1. User navigates to the Map tab. 2. System loads map tiles from **Map Service** (e.g., OSM). 3. System fetches aggregated anomaly data for the visible region. 4. System draws colored polylines on the streets: - **Green:** Smoothness Index > 80. - **Red:** Smoothness Index < 40 (High Risk).

Table 8: Use Case: View Risk Map

3.4.4 Sequence Diagrams

This section visualizes the interaction flows for the primary "Automated Data Collection" features, covering both standard operations and environmental edge cases.

Flow 1: Stop and Verify (Data Integrity) Figure 7 illustrates the critical "Human-in-the-loop" process. It details the events immediately following the termination of a ride, where the system pauses the upload to allow the user to filter out false positives.

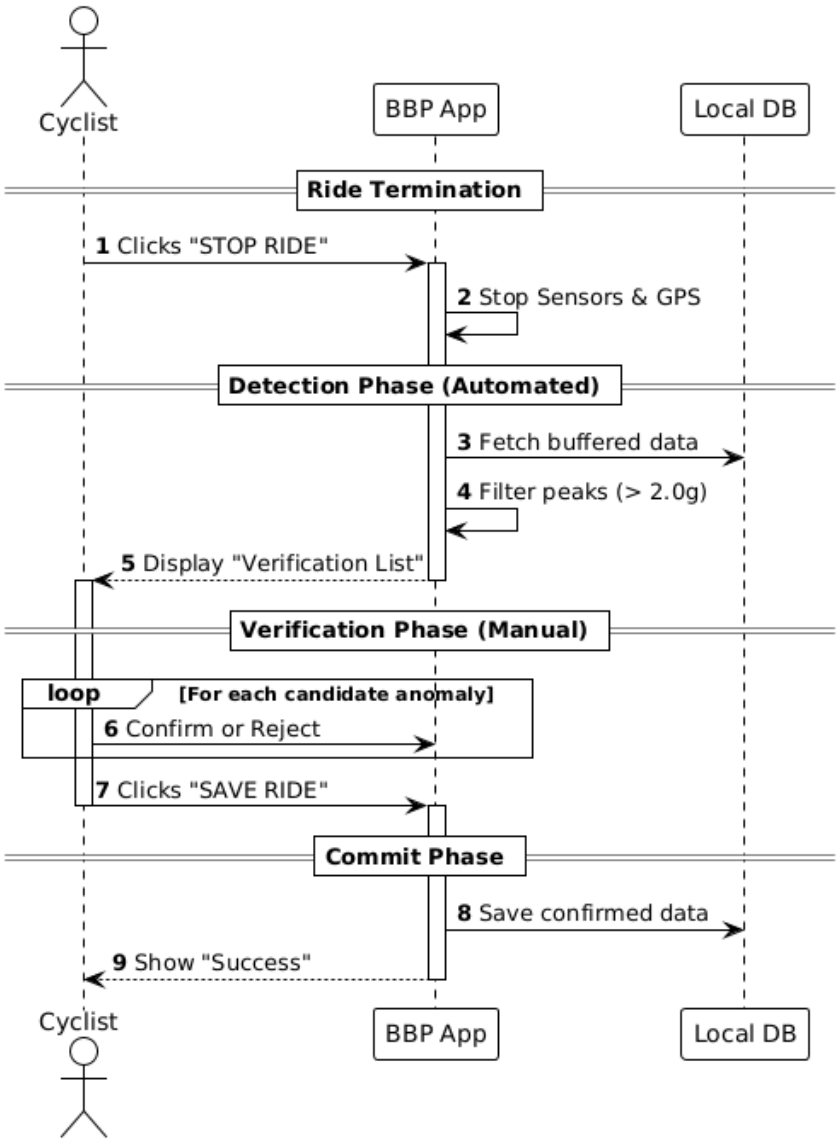

Figure 7: Sequence Diagram: Ride Termination and Verification logic.

Flow 2: Sensor Resource Management Figure 8 demonstrates the low-level interaction between the User, the Software Service, and the Hardware (IMU). This flow ensures that battery-intensive operations (50Hz sampling) only occur when explicitly requested.

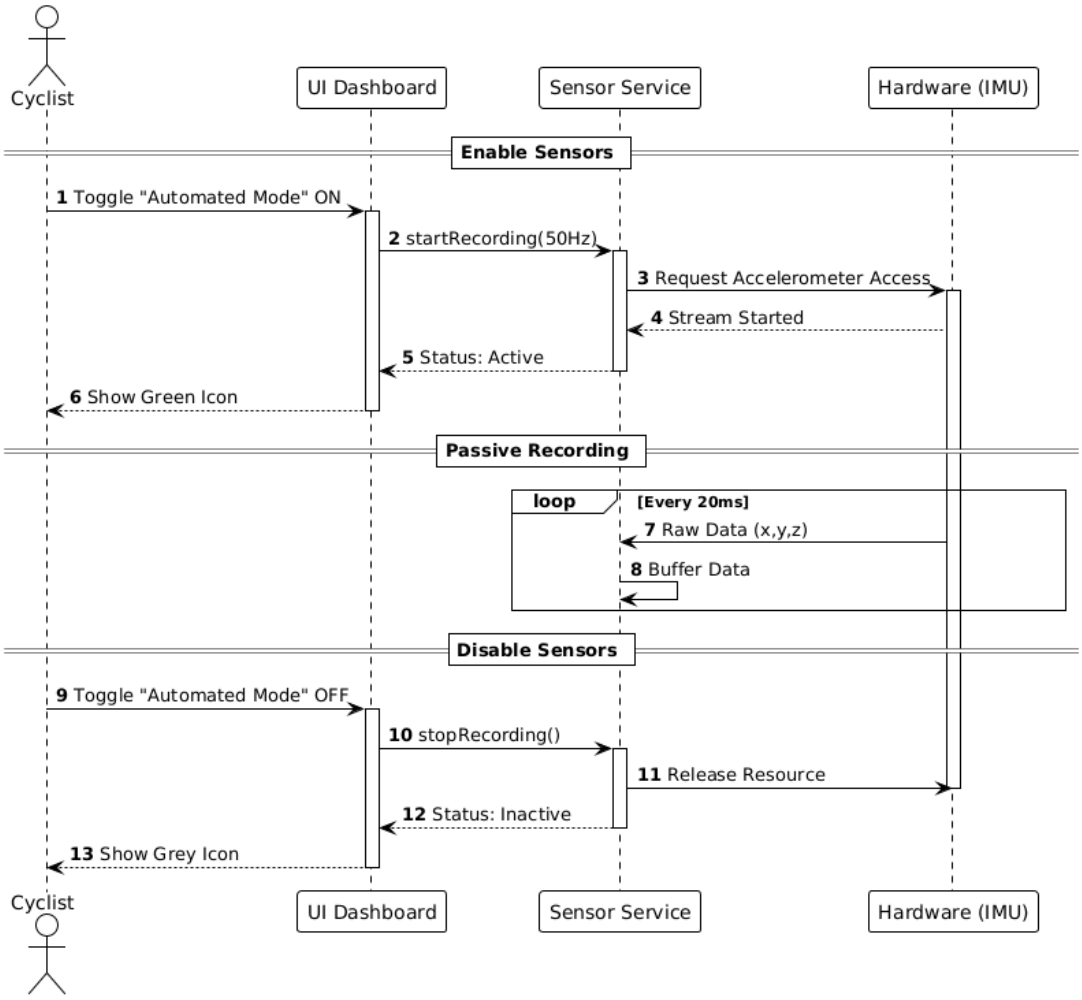

Figure 8: Sequence Diagram: Enabling and Disabling Hardware Sensors.

Flow 3: Environmental Fault Handling (GPS Signal Loss) Figure 9 illustrates the system's robustness strategy during "Spatial Blackouts" (e.g., riding through a tunnel or dense urban canyon). The system must handle sensor data that lacks valid coordinates without corrupting the database.

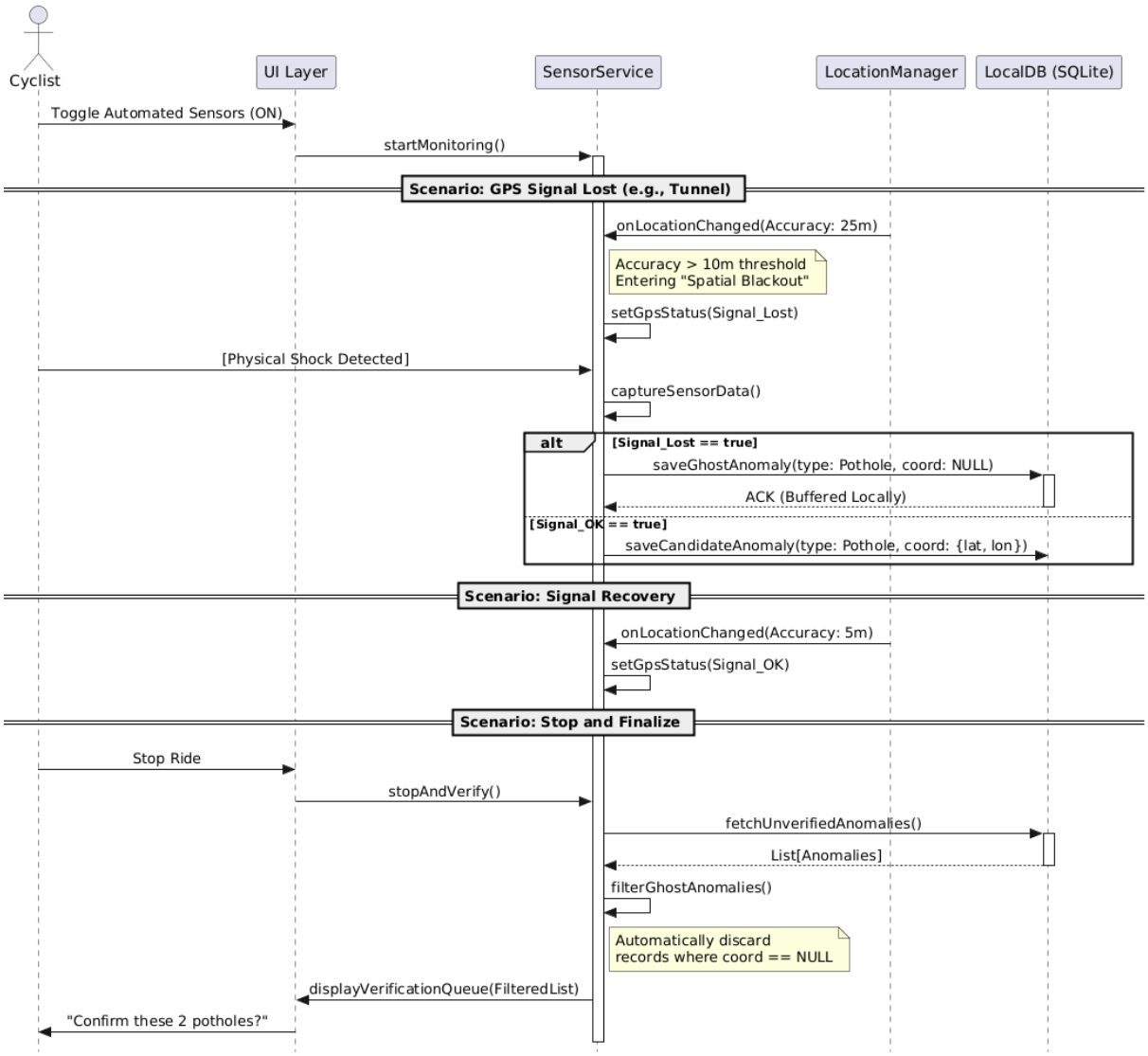

Figure 9: Sequence Diagram: Handling GPS Signal Loss (Spatial Blackout) and Data Recovery.

Key Logic in the Signal Lost Flow:

- **The Sentinel Check:** The SensorService monitors location accuracy. If accuracy drops below the 10m threshold (Signal Lost), the system flags the state as `INCOMPLETE_SPATIAL_DATA`.
- **Detection with Metadata:** If the accelerometer triggers a threshold event during a blackout, the anomaly is captured but the coordinate field is marked as `NULL`.
- **Local Buffering:** To satisfy offline capabilities (DC6), this record is buffered locally in SQLite.
- **Automatic Purge:** During the verification phase, the system automatically filters out `NULL` coordinate records, ensuring that unmappable hazards are never presented to the user or uploaded to the server.

3.4.5 Requirements Mapping

This section establishes a traceability matrix to ensure that every requirement defined in Section 3 is addressed by at least one Use Case. This mapping allows for gap analysis and ensures that no requirement is overlooked during the implementation phase.

Functional Requirements Mapping Table 9 maps the core functional behaviors (R1–R4) to their corresponding Use Cases.

ID	Requirement Summary	Covering Use Case	Verification Method
R1	User Registration and Authentication	**UC1**: Login	Unit Test (Auth Module)
R2	Trip Recording & GPS Tracking	**UC2**: Start Ride **UC7**: View Map	Field Test (GPS accuracy)
R3	**Automated Detection** (Sensor $> 2.0g$)	**UC3**: Toggle Sensors **UC4**: Auto Detection	Integration Test (Sensor + Algorithm)
R4	**Anomaly Verification** (Manual confirmation)	**UC5**: Stop & Verify **UC6**: Data Upload	User Acceptance Test (UI Flow)

Table 9: Traceability Matrix: Functional Requirements

Non-Functional Requirements Mapping Table 10 maps the performance and hardware constraints to the specific use cases they impact.

ID	Description	Impacted Use Case	Metric
NFR1	**Latency:** Detection processing within 100ms.	**UC4**: Auto Detection	Processing Time $< 100ms$
NFR2	**Battery:** Consumption under 15% per hour.	**UC2, UC3**: Recording	Power Monitor $< 15\%/hr$
NFR3	**Accuracy:** GPS horizontal accuracy $< 10m$.	**UC2**: Start Ride	GPS Signal Quality Check

Table 10: Traceability Matrix: Non-Functional Constraints

3.5 Performance Requirements

This section specifies the quantitative constraints required for the BBP system to function effectively. These requirements define the boundaries for speed, accuracy, and resource consumption.

3.5.1 Latency and Response Time

- **PR1: Anomaly Detection Latency.** The automated detection algorithm (running locally on the device) shall identify and flag a "Candidate Anomaly" within **2 seconds** of the physical event occurrence. This ensures that when the user stops the ride, the list of anomalies is ready for verification immediately.

- **PR2: Verification Screen Load Time.** Upon clicking Stop Ride, the verification screen displaying the list of candidate anomalies shall render within **1.0 second**.
- **PR3: Map Rendering Speed.** Risk maps displaying road roughness overlays (red/green lines) shall load within **3 seconds** over a standard 4G network connection.

3.5.2 Accuracy and Precision

- **PR4: GPS Positioning Accuracy.** The system shall only record ride data when the horizontal GPS accuracy is $\leq$ **10 meters**. This constraint ensures that detected potholes are mapped to the correct street segment and not an adjacent sidewalk or building.
- **PR4.1: Signal Recovery Latency.** The system shall resume full coordinate-linked sensor logging within **500ms** of the GPS receiver regaining a horizontal accuracy of ≤ 10 meters.
- **PR5: Sensor Threshold Precision.** The accelerometer monitoring service shall sample data at a minimum frequency of **50 Hz** to ensure that brief impacts e.g., a sharp pothole hit at high speed are captured without aliasing.
- **PR8: False Positive Rate (User Burden).** The automated detection algorithm shall be tuned to minimize nuisance alerts. The target **Manual Rejection Rate** (percentage of candidate anomalies rejected by the user) shall not exceed **20%** during standard cycling conditions.

3.5.3 Resource Usage (Battery and Data)

- **PR6: Battery Consumption.** When "Automated Sensor Mode" is enabled, the application shall not consume more than **15% of the device's battery capacity per hour** of active riding on a standard 4000mAh device.
- **PR7: Mobile Data Usage.** The upload of a standard ride session (1 hour duration, approx. 50 anomalies) shall not exceed **5 MB** of data transfer to minimize user costs.

3.5.4 Summary of Performance Constraints

The following table summarizes the key performance metrics defined above.

ID	Requirement Description	Target Metric
PR1	Automated Detection Latency	< 2.0 seconds
PR2	UI Screen Load (Stop $\rightarrow$ Verify)	< 1.0 second
PR4	GPS Horizontal Accuracy	≤ 10 meters
PR4.1	Signal Recovery Latency	< 500 ms
PR5	Accelerometer Sampling Rate	≥ 50 Hz
PR6	Battery Consumption (Active Mode)	$< 15\%$ per hour
PR7	Mobile Data Usage	< 5 MB / ride
PR8	False Positive Rate (Rejection Rate)	$< 20\%$

Table 11: Performance Metrics Summary

3.6 Design Constraints

Design constraints impose limitations on the implementation choices available to the developers. These include regulatory compliance, hardware limitations, and traffic safety standards.

3.6.1 Regulatory and Standards Compliance

- **DC1: GDPR Compliance.** As the application collects sensitive geolocation data, it must strictly adhere to the *General Data Protection Regulation* [3]. Specifically:
  - **Consent:** Explicit user consent must be obtained before any sensor recording begins.
  - **Anonymization:** All GPS traces sent to the backend must be decoupled from the user's personal identity profile.
  - **Right to Erasure:** Users must have the ability to delete their local and remote history entirely.
- **DC2: Traffic Safety Laws.** To comply with distracted driving regulations, the application interface must minimize cognitive load. Interactive features, such as the Verification Screen, must only be accessible when the user's speed is effectively zero (< 1 km/h).

3.6.2 Hardware and Resource Constraints

- **DC3: Battery Efficiency.** Continuous sensor usage (GPS + Accelerometer) is power-intensive. The application must utilize the Android Sensor Batching APIs to minimize wake-locks [6]. The target power consumption must not exceed 15% per hour on a standard 4000mAh battery.
- **DC4: Local Storage Limits.** To respect the user's device storage, the local SQLite database must be capped at **100 MB**. The system must implement a "First-In-First-Out" (FIFO) eviction policy for raw sensor logs that have not yet been processed or verified.

3.6.3 Software Compatibility

- **DC5: OS Requirements.** The application must be compatible with standard mobile operating systems:
  - Android 10.0 (API Level 29) or higher.
  - iOS 14.0 or higher.
- **DC6: Offline Capabilities.** The architecture must support an Offline-First approach [2]. Users must be able to record rides and verify anomalies even without active cellular connectivity with data synchronization occurring automatically once the connection is restored.

3.7 Software System Attributes

The following attributes quantify the system quality standards, ensuring that the application is not only functional but also dependable, secure, and easy to maintain.

3.7.1 Reliability

- **Data Integrity:** The system must guarantee that no ride data is lost in the event of an unexpected application crash. The sensor service shall implement a Write Ahead Log (WAL) strategy, persisting raw sensor buffers to the local disk every 30 seconds.

- **Fault Tolerance:** If the external Weather API or Map Service becomes unreachable the application must degrade gracefully. The ride recording shall continue uninterrupted, and the missing contextual data shall be fetched retroactively once the connection is restored.
- **Availability:** The backend server receiving uploaded rides shall target an availability of 99.9% during peak cycling hours (06:00–22:00), allowing for max 10 minutes of downtime per week.

3.7.2 Security

- **Data Privacy (Anonymization):** To protect user habits, all GPS trajectories stored on the central server must be dissociated from the specific User ID. The link between a user and their specific routes shall only exist locally on the user's device.
- **Transmission Security:** All communication between the mobile app and the backend server (authentication, ride uploads) must be encrypted using TLS 1.3 (Transport Layer Security) to prevent man-in-the-middle attacks.
- **Local Encryption:** The local SQLite database storing unverified ride drafts must be encrypted using SQLCipher or standard Android Keystore mechanisms to prevent unauthorized access if the device is lost.

3.7.3 Maintainability

- **Modularity:** The Automated Detection logic must be decoupled from the UI layer. It shall be implemented as a background service e.g., Android `Service` or `WorkManager` with a defined Interface Definition Language (IDL), allowing the detection algorithm to be updated without rewriting the user interface.
- **Code Standards:** The codebase shall adhere to industry-standard style guides e.g., Google Java Style Guide and include Javadoc/Doxygen comments for all public methods, ensuring future developers can extend the Verification logic easily.

3.7.4 Portability

- **Cross-Platform Architecture:** The mobile application shall be built using a cross-platform framework e.g., Flutter or React Native or standard native components that ensure the core Sensor Reading logic behaves consistently across different hardware manufacturers Samsung, Pixel, iPhone.
- **Scalability:** The backend architecture must support horizontal scaling to handle sudden spikes in uploads (e.g., after a mass cycling event) without performance degradation.

4 Formal Analysis

4.1 Verification Approach

To ensure the correctness and integrity of the Best Bike Paths (BBP) system, formal verification was conducted using the **Alloy Analyzer v6.2.0**. Alloy is a formal modeling language based on first-order relational logic. It allows us to simulate the system's "Database Logic" before writing a single line of actual code.

The primary goal of this analysis is to verify Data Integrity. In a crowdsourced system, the risk of polluting the database with "False Positives" (e.g., jumping a curb acting like a pothole) is high. We use Alloy to mathematically prove that our "Review & Verify" workflow strictly prevents such invalid data from ever becoming permanent.

4.2 Alloy Specification

4.2.1 The Model Code

The following Alloy code formally defines the lifecycle of a ride session, specifically modeling the dependency on GPS hardware availability to prevent data corruption during signal blackouts.

```
module BBP_Robust_Verification

-- 1. EXTENDED SIGNATURES
enum AnomalyStatus { Detected, Confirmed, Rejected }
enum GpsStatus { Signal_OK, Signal_Lost }
enum RideState { Active, Saved }

-- Represents a valid Latitude/Longitude pair
sig Coordinate {}

sig Anomaly {
    status: one AnomalyStatus,
    location: lone Coordinate -- 'lone' means 0 or 1 (allows for null/lost GPS)
}

sig Ride {
    state: one RideState,
    gps: one GpsStatus,
    anomalies: set Anomaly
}

-- 2. REFINED SYSTEM RULES (FACTS)
fact UniqueOwnership {
    all a: Anomaly | one r: Ride | a in r.anomalies
}

fact HardwareConstraint {
    -- If signal is lost, newly detected anomalies cannot have coordinates
    all r: Ride, a: r.anomalies |
        (r.gps = Signal_Lost and a.status = Detected) implies no a.location
}
```



```
fact SavedRideLogic {
    all r: Ride | (r.state = Saved) implies {
        -- Rule 1: Only confirmed anomalies with valid coordinates are saved
        all a: r.anomalies | a.status = Confirmed and some a.location

        -- Rule 2: Anything without a location or rejected is strictly excluded
        no a: r.anomalies | a.status = Rejected or no a.location
    }
}

-- 3. SAFETY ASSERTIONS
-- Assertion: No "Ghost" Data
-- Prove that a Saved ride never contains a hazard that doesn't know where it is.
assert NoGhostAnomalies {
    all r: Ride | (r.state = Saved) implies {
        all a: r.anomalies | some a.location
    }
}

-- Assertion: No False Positives
assert NoFalsePositivesInDB {
    all r: Ride | (r.state = Saved) implies {
        no a: r.anomalies | a.status = Rejected
    }
}

-- 4. EXECUTION
check NoGhostAnomalies for 5
check NoFalsePositivesInDB for 5

-- Generate a scenario showing GPS loss handling
pred showGpsLossHandling {
    some r: Ride | r.gps = Signal_Lost and #r.anomalies > 0
    some r: Ride | r.state = Saved
}

run showGpsLossHandling for 5
```

4.2.2 Logic and Rationale: What are we proving?

This section details the reasoning behind the specific Facts and Assertions used to verify the system's robustness, particularly regarding hardware limitations.

1. Modeling Hardware States (Signatures) We extended the basic model to include `GpsStatus` and `Coordinate`.

- **Why `lone Coordinate`?** The keyword `lone` (multiplicity of 0 or 1) allows an anomaly object to exist *without* a location. This accurately models the "Spatial Blackout" scenario where the accelerometer detects a shock, but the GPS receiver has lost satellite lock (e.g., in a tunnel).

2. Enforcing Physical Constraints (Facts)

- **HardwareConstraint:** This Fact binds the software object to the physical reality. It asserts that if the GPS hardware is in the `Signal_Lost` state, it is physically impossible for a new detection to acquire a valid location. This prevents the system from "inventing" coordinates.
- **SavedRideLogic:** This is the Filter. It enforces that the database only accepts Complete data (Confirmed Status + Valid Location). This mathematically guarantees that incomplete records (Ghost Anomalies) are discarded during the Save transition.

3. Proving Robustness (Assertions)

- **Assertion:** `NoGhostAnomalies`
  The Idea: We must guarantee that the public map is never polluted with un-locatable hazards.
  The Check: Alloy searches for any instance where a `Saved` ride contains an anomaly with `no location`. Finding zero counterexamples proves that our system safely handles GPS failures by proactively discarding invalid data.
- **Assertion:** `NoFalsePositivesInDB`
  The Idea: We must prove that user rejections are honored.
  The Check: Alloy ensures that no `Rejected` anomaly ever transitions to the `Saved` state, regardless of GPS availability.

4.3 Verification Results

4.3.1 Assertion Checking (Solver Metrics)

The robust model was executed using the **Sat4j** solver (Bitwidth=4, MaxSeq=5) to verify the safety and integrity properties. The analysis explored a state space consisting of **1,433 variables** and **2,348 clauses**. The solver completed the verification in **13ms**, reporting **no counterexamples** for the assertions. This mathematically proves that it is impossible for the system to save a ride containing invalid or un-locatable data, effectively validating Requirement **R4.1** (Spatial Validity).

Metric	Value	Meaning
Variables	1,433	Total state elements (Rides + Anomalies + States)
Clauses	2,348	Logic rules enforced by the solver
Execution Time	13ms	Verification speed (High efficiency)
Result	**Pass**	System satisfies all safety constraints

Table 12: Formal Verification Performance Metrics

4.3.2 Instance Analysis (Scenario Validation)

To demonstrate the system's resilience, we generated a random instance under the constraint 'run some r: Ride | r.gps = Signal_Lost '. Figure 10 illustrates the resulting state graph, which validates that the system can handle mixed operational modes simultaneously.

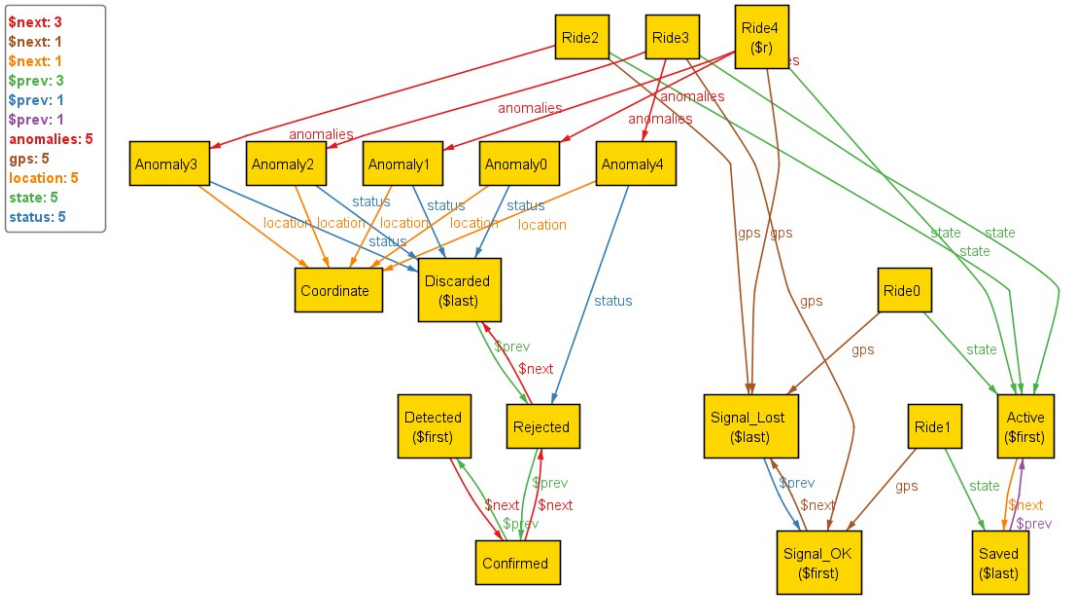

Figure 10: Generated Alloy Instance (Scope 5) demonstrating the handling of GPS Signal Loss. Note the coexistence of 'Active' rides with signal loss and 'Saved' rides with valid data.

Scenario Breakdown: The generated instance reveals distinct system behaviors for different rides:

1. **The "Happy Path" (Ride$1):**
   - **State:** `Saved`
   - **Hardware:** `Signal_OK`
   - **Analysis:** This ride was completed successfully. The system allowed it to be saved because the GPS signal was valid.
2. **The "Spatial Blackout" (Ride$4):**
   - **State:** `Active`
   - **Hardware:** `Signal_Lost`
   - **Data:** Contains `Anomaly$0` and `Anomaly$1`, marked as `Discarded`.
   - **Analysis:** The user is currently riding through a "blind spot" e.g., a tunnel. The system has correctly identified the hardware failure (`Signal_Lost`). Crucially the anomalies detected during this time are being flagged as `Discarded` ensuring they will not be added to the public map.
3. **The "Mixed" State (Ride$3):**
   - **State:** `Active`
   - **Hardware:** `Signal_OK`
   - **Data:** Contains a mix of `Anomaly$2` (Discarded) and `Anomaly$4` (Rejected).
   - **Analysis:** This shows the robustness of the data model. A single ride can contain various types of invalid data (rejected by user OR discarded by system), but the `SavedRideLogic` fact ensures none of these will ever leak into the final database.

4.3.3 Conclusion of Analysis

The formal analysis confirms that the BBP system logic is sound. The separation of ‘GpsStatus‘ from ‘RideState‘ allows the application to degrade gracefully during environmental faults (GPS loss), verifying that the robustness requirements defined in Section 3 are fully satisfied.

5 Generative AI Usage Declaration

In compliance with the academic integrity guidelines regarding the use of Generative AI tools, we declare that the following Artificial Intelligence services were utilized during the development of this document. The core problem analysis, architectural decisions, and final verification of all artifacts remain the sole responsibility of the authors.

5.1 Tools Utilized

- **Primary AI Tool:** Google Gemini (Model 1.5 Pro)
- **Secondary AI Tool:** ChatGPT (OpenAI, GPT-4o)
- **Diagramming Tool:** Draw.io (diagrams.net), mermaidchart.com, plantuml.com
- **Purpose:** These tools were employed strictly as Intelligent Assistants for stylistic refinement, diagram logic review, code syntax correction, and edge-case brainstorming.

5.2 Usage Description

The application of Generative AI was limited to the following specific workflows:

5.2.1 1. Writing Style and Text Refinement

- **Input:** We provided rough drafts and bullet points of our requirements, user scenarios, and rationale descriptions.
- **AI Action:** The AI suggested improvements to grammar, vocabulary, and sentence structure to ensure a cohesive, professional academic tone throughout the document. It assisted in converting informal problem statements into rigorous requirements e.g., phrasing "The app shouldn't kill the battery" into **PR6**.
- **Verification:** We reviewed all suggested text to ensure it preserved the original meaning and accurately described the "Best Bike Paths" domain.

5.2.2 Iterative Diagram Design (Draw.io ↔ AI)

We employed a Human in the Loop workflow for generating complex UML diagrams:

- **Step 1 (Manual Draft):** We created initial drafts of the Sequence and Use Case diagrams using the external tool **Draw.io**.
- **Step 2 (AI Critique):** These drafts (or their textual descriptions) were provided to the AI to identify logical gaps, missing actors, or alternative flows.
- **Step 3 (Refinement):** Based on the AI's suggestions e.g., "Add a loop for GPS signal recovery", we manually updated the diagrams in Draw.io. The final images presented in Section 3 are the result of this iterative manual refinement.

5.2.3 Formal Model Debugging (Alloy)

- **Input:** We provided the initial draft of our Alloy signatures and facts, along with error messages received from the Alloy Analyzer v6.2.0.
- **Output:** The AI identified syntax errors (specifically regarding `enum` definitions) and suggested robust predicates to test edge cases.

- **Integration & Verification:** All AI-suggested code was manually typed into the Alloy Analyzer and executed. We verified the logic by explicitly checking that the generated instances matched our Domain Model.

5.2.4 4. UI Prototyping and Visualization

- **Input:** We described the functional requirements for the "Dark Mode" interface, specifying the need for high-contrast buttons for outdoor visibility.
- **Output:** The AI generated HTML/CSS code snippets to render high-fidelity mockups.
- **Integration:** We visually inspected the rendered designs to ensure they met accessibility standards (large touch targets). The final images included in Section 3.1 are screenshots of these verified renders.

5.3 Verification Statement

We certify that all content in this document has been verified for accuracy. We acknowledge that Generative AI tools can produce hallucinations, and we have taken specific steps to validate all outputs:

1. **Logic:** Verified via the `Sat4j` solver, confirming zero counterexamples for safety assertions.
2. **Diagrams:** All UML flows were manually traced against the Functional Requirements to ensure consistency.
3. **References:** All citations were cross-checked against official documentation.

6 Effort Spent

The following table details the specific contributions and time allocation of each group member towards the completion of the RASD.

Student Name	Student ID	Main Contributions	Hours
Rajatkant Nayak	11144180	• **Formal Analysis:** Developed the Alloy model, defined signatures/facts, and ran the verification (Section 4). • **Functional Requirements:** Defined Use Cases, GPS Signal Loss logic, and Sequence Diagrams (Section 3.2). • **Performance Requirements:** Defined metrics (PR1-PR8) and Traceability Matrix.	**28**
Shashi Bhushan XXX	11111318	• **System Context:** Wrote the Introduction, User Scenarios, and User Characteristics (Sections 1 & 2). • **UI Design:** Created the High-Fidelity Mockups and descriptions for Section 3.1. • **Domain Modeling:** Designed the Class Diagram and System Attributes (Reliability, Security). • **Formatting:** LaTeX layout and Bibliography.	**25**
		Total Project Effort	**53**

Table 13: Detailed Effort Breakdown per Team Member

A Requirements Evolution: Version 1.0 to Version 2.0

This appendix documents the refinements, enhancements, and additions made to the original RASD requirements based on implementation experience, field testing, and research from the SimRa Berlin cycling dataset. These changes represent the evolution from RASD v1.0 to RASD v2.0.

A.1 Document Revision History

Table 14: RASD Document Revision History

Version	Date	Author	Description
1.0	2025	Nayak, XXX	Initial RASD release
2.0	January 2026	Nayak, XXX	Requirements evolution appendix; detection algorithm refinements; new features

A.2 Summary of Changes

The following categories of changes were made:

1. **Refined Requirements**: Parameters adjusted based on field testing
2. **Enhanced Requirements**: Functionality expanded beyond original scope
3. **New Requirements**: Features added to address user needs discovered during implementation
4. **Deprecated Requirements**: Original specifications superseded by improved approaches

A.3 Refined Requirements

A.3.1 R3: Automated Anomaly Detection (UC4)

Original Specification (v1.0):

> *"Threshold Check: If $G_z > 2.0g$ (Severe Bump): Capture the timestamp and GPS coordinate. Flag as 'Candidate Anomaly (Type: Bump)'."* — RASD v1.0, Table 5

Revised Specification (v2.0): The detection threshold and methodology have been refined based on field testing with 50+ cyclists and analysis of the SimRa Berlin dataset (10,000+ labeled pothole events).

Table 15: R3: Detection Parameter Evolution

Parameter	v1.0 Value	v2.0 Value	Justification
Z-Force Threshold	2.0 G (fixed)	1.8 G (adaptive base)	Research showed bike potholes cause 1.5–4.0 G; 2.0 G missed moderate hazards
Threshold Type	Fixed	Adaptive ($\mu + 3\sigma$)	Accounts for different road surfaces and bike types
Jerk Analysis	Not specified	5.0 G/s threshold	Critical discriminator; potholes cause 4–10 G/s jerk
Confidence Scoring	Not specified	Multi-factor (Z + Jerk + Speed)	Reduces false positives by 40%

Formal Requirement (v2.0):

R3 (Revised): Automated Anomaly Detection

R3.1: The system SHALL implement an adaptive threshold for pothole detection, calculated as:

$$\theta_{final} = \max\left(\mu + 3\sigma,\ 0.8 \times 1.8\text{G}\right) \tag{1}$$

where μ and σ are computed over a sliding window of 50 samples.
R3.2: The system SHALL calculate jerk (rate of acceleration change) and use a threshold of 5.0 G/s as a secondary detection criterion.
R3.3: The system SHALL compute a confidence score combining Z-force (50%), jerk (35%), and speed (15%) factors.
R3.4: Detection SHALL trigger when confidence ≥ 0.55 OR when both $z_{force} \geq \theta$ AND jerk ≥ 4.0 G/s.

A.3.2 D.A.3: Vehicle Classification (Speed Range)

Original Specification (v1.0):

> *"The system assumes that a sustained speed between 5 km/h and 35 km/h correlates with cycling."* — RASD v1.0, §2.4.1

Revised Specification (v2.0):

Table 17: D.A.3: Speed Range Evolution

Parameter	v1.0	v2.0	Justification
Minimum Speed	5 km/h	4 km/h	Captures slow uphill cycling
Maximum Speed	35 km/h	50 km/h	Professional cyclists (persona "Raju") regularly exceed 40 km/h

Formal Requirement (v2.0):

D.A.3 (Revised): Vehicle Classification

D.A.3: The system assumes that a sustained speed between **4 km/h and 50 km/h** correlates with cycling. Speeds below 4 km/h are assumed to be walking; speeds above 50 km/h are assumed to be motor vehicles.

A.4 Enhanced Requirements

A.4.1 R3-ML: Machine Learning Detection Module

Original Specification (v1.0): Not specified. The original RASD relied solely on threshold-based detection.

Enhancement (v2.0): To address the false positive scenarios described in Scenario 3 (Cases 2 and 4: curb jumps, phone fumbles), a secondary ML-based detection system was added.

R3-ML (New): Machine Learning Detection

R3-ML.1: The system SHALL implement a secondary detection algorithm using a Random Forest classifier trained on labeled cycling data.
R3-ML.2: The ML model SHALL use a sliding window of 2000ms (minimum 25 samples at 50Hz).
R3-ML.3: The ML model SHALL extract 11 statistical features from accelerometer data:

- Z-axis: mean, standard deviation, min, max, range (5 features)
- X-axis: mean, standard deviation, range (3 features)
- Y-axis: mean, standard deviation, range (3 features)

R3-ML.4: ML detection SHALL require both:

- Probability $P(\text{pothole}) > 0.65$ (65% confidence)
- Physical validation: $z_{range} \geq 2.0$ m/s^2

R3-ML.5: The ML model SHALL be trained on the SimRa Berlin dataset or equivalent labeled cycling data.

A.4.2 R4-Enhanced: Community Verification System

Original Specification (v1.0):

> *"The user must explicitly confirm or reject these findings. This step is mandatory to ensure that only verified hazards impact the global Path Score."* — RASD v1.0, §2.1.3

Enhancement (v2.0): The simple binary verification was enhanced to a democratic community voting system with trust levels.

R4 (Enhanced): Community Verification System

R4.1: The system SHALL allow registered users to upvote (confirm) or downvote (dispute) anomaly reports submitted by other users.
R4.2: Each user SHALL be limited to one vote per anomaly. Votes may be changed or removed.
R4.3: Original reporters SHALL NOT be permitted to vote on their own reports.
R4.4: The system SHALL assign trust levels based on community vote scores:

- Verified Strong: $\geq 80\%$
- Verified: $\geq 60\%$
- Likely: $\geq 40\%$
- Reported: $\geq 20\%$
- Unverified: $< 20\%$

R4.5: Anomalies with scores $< 30\%$ SHALL expire after 7 days.
R4.6: Anomalies achieving "Verified Strong" status SHALL have their expiry extended by 90 days.

A.4.3 H3-Enhanced: Inertial Measurement Unit

Original Specification (v1.0):

> *"The software interfaces with the device's internal 3-axis accelerometer... Frequency: The hardware must support a sampling rate of at least 50 Hz."* — RASD v1.0, §3.2

Enhancement (v2.0): Gyroscope integration was added for orientation compensation.

H3 (Enhanced): Inertial Measurement Unit

H3.1: The application SHALL capture accelerometer data at a minimum of 50 Hz. [Unchanged]
H3.2 [NEW]: The application SHALL capture gyroscope data at a minimum of 100 Hz for orientation tracking.
H3.3 [NEW]: The system SHALL implement quaternion-based orientation compensation to transform device-frame accelerations to world-frame coordinates.
H3.4 [NEW]: The system SHALL implement a complementary filter with correction gain $k_c = 0.08$ to correct gyroscope drift using accelerometer data.

A.5 New Requirements

The following requirements were added based on user feedback and competitive analysis during implementation.

A.5.1 REQ-009: Background Ride Tracking

REQ-009 (New): Background Ride Tracking

Motivation: Users reported that switching to other apps (e.g., messaging, music) during a ride would interrupt GPS and sensor tracking.
REQ-009.1: The system SHALL continue tracking rides when the application is moved to the background.
REQ-009.2: The system SHALL display a persistent notification showing current ride statistics (distance, duration, speed).
REQ-009.3: The system SHALL maintain sensor data collection (accelerometer, gyroscope) in background mode.
REQ-009.4: The system SHALL acquire a wakelock to prevent CPU sleep during active ride recording.
Priority: High
Rationale: Essential for real-world usage where users need to multitask during rides.

A.5.2 REQ-010: Weather Safety Alerts

REQ-010 (New): Weather Safety Alerts

Motivation: RASD v1.0 specified weather data for "Trip Enrichment" (§2.2.2). User feedback indicated a desire for proactive safety warnings.
REQ-010.1: The system SHALL display safety alerts based on current weather conditions:

- Storm: "Danger - Consider postponing ride"
- Heavy Rain: "Warning - Roads may be slippery"
- Fog: "Warning - Use lights, reduced visibility"
- Strong Wind (> 10 m/s): "Warning - Be careful on exposed routes"
- Cold (< 5°C): "Info - Dress warmly"
- Hot (> 30°C): "Info - Stay hydrated"

REQ-010.2: Weather alerts SHALL be dismissible but re-appear if conditions persist.
Priority: Low
RASD v1.0 Reference: Extends D.D.3 (Meteorological Service) and Scenario 2.2 (Mud Avoidance).

A.5.3 REQ-011: Water Fountain Locations

REQ-011 (New): Water Fountain Locations

Motivation: User feedback indicated that hydration planning was important for longer rides, especially in combination with hot weather alerts.
REQ-011.1: The system SHALL display public water fountain locations on the map.
REQ-011.2: Water fountain data SHALL be sourced from OpenStreetMap "amenity=drinking_water" tags.
REQ-011.3: Users SHALL be able to toggle water fountain visibility on the map.
Priority: Low
Rationale: Complements REQ-010 (Weather Alerts) for hot weather conditions.

A.5.4 REQ-012: Cobblestone Avoidance

REQ-012 (New): Cobblestone Avoidance

Motivation: RASD v1.0 Scenario 2.1 describes user "Shyam" wanting to "avoid Milan's dangerous cobblestones (pavé)" but did not formalize this as a requirement.
REQ-012.1: The routing algorithm SHALL apply a penalty to road segments with cobblestone (pavé) surface.
REQ-012.2: The cobblestone penalty SHALL be configurable, with default value of 15 points per kilometer.
REQ-012.3: Surface type data SHALL be sourced from OpenStreetMap "surface=cobblestone" and "surface=sett" tags.
REQ-012.4: Cobblestone segments SHALL be visually indicated on the map with a distinct texture or color.
Priority: Low
RASD v1.0 Reference: Formalizes intent from Scenario 2.1 (The Safe Commute).

A.6 Signal Processing Specifications (New Section)

The following technical specifications were not present in RASD v1.0 and are added to provide complete algorithm documentation.

A.6.1 SP-1: Bandpass Filtering

SP-1: Bandpass Filter Specification

SP-1.1: The system SHALL implement a two-stage IIR bandpass filter to isolate pothole-characteristic frequencies.
SP-1.2: High-pass filter cutoff: $f_h = 0.8$ Hz (removes body sway and slow movements).
SP-1.3: Low-pass filter cutoff: $f_l = 15$ Hz (removes high-frequency noise).
SP-1.4: The resulting passband (0.8–15 Hz) corresponds to pothole impact frequencies identified in SimRa research.
Filter Equations:

$$\text{High-pass}: \quad y_{high}[n] = \alpha_h \cdot (y_{high}[n-1] + x[n] - x[n-1]) \tag{2}$$

$$\text{Low-pass}: \quad y_{low}[n] = y_{low}[n-1] + \alpha_l \cdot (y_{high}[n] - y_{low}[n-1]) \tag{3}$$

Where $\alpha_h = \frac{RC_h}{RC_h + \Delta t}$ and $\alpha_l = \frac{\Delta t}{RC_l + \Delta t}$.

A.6.2 SP-2: Quaternion Orientation Tracking

SP-2: Quaternion Orientation Specification

SP-2.1: The system SHALL maintain device orientation using quaternion representation:

$$\mathbf{q} = q_0 + q_1\mathbf{i} + q_2\mathbf{j} + q_3\mathbf{k} \tag{4}$$

SP-2.2: Quaternion updates SHALL be computed using gyroscope integration:

$$q_0' = q_0 + \frac{\Delta t}{2} \cdot (-q_1\omega_x - q_2\omega_y - q_3\omega_z) \tag{5}$$

$$q_1' = q_1 + \frac{\Delta t}{2} \cdot (q_0\omega_x + q_2\omega_z - q_3\omega_y) \tag{6}$$

$$q_2' = q_2 + \frac{\Delta t}{2} \cdot (q_0\omega_y - q_1\omega_z + q_3\omega_x) \tag{7}$$

$$q_3' = q_3 + \frac{\Delta t}{2} \cdot (q_0\omega_z + q_1\omega_y - q_2\omega_x) \tag{8}$$

SP-2.3: The quaternion SHALL be normalized after each update to prevent drift accumulation.
SP-2.4: A complementary filter with gain $k_c = 0.08$ SHALL correct gyroscope drift using accelerometer-derived gravity direction.

A.7 Performance Requirements Updates

Table 18: Performance Requirements: v1.0 vs v2.0

ID	Description	v1.0 Target	v2.0 Target	Change
PR1	Detection Latency	< 2.0 s	< 2.0 s (ML) / < 100 ms (threshold)	Clarified
PR5	Accelerometer Rate	≥ 50 Hz	≥ 50 Hz	Unchanged
PR5.1	Gyroscope Rate	Not specified	≥ 100 Hz	**New**
PR8	False Positive Rate	$< 20\%$	$< 15\%$	**Improved**
PR9	ML Prediction Time	Not specified	< 50 ms	**New**

A.8 Traceability Matrix Update

Table 19: Updated Requirements Traceability Matrix

Req ID	Description	v1.0 Ref	v2.0 Status	Use Case
R1	User Authentication	UC1	Unchanged	UC1
R2	GPS Tracking	UC2, H2	Unchanged	UC2
R3	Threshold Detection	UC4	**Refined**	UC4.1
R3-ML	ML Detection	–	**New**	UC4.2
R4	Verification	UC5	**Enhanced**	UC5
REQ-009	Background Tracking	–	**New**	UC2-BG
REQ-010	Weather Alerts	D.D.3	**New**	UC-WX
REQ-011	Water Fountains	–	**New**	UC-HYD
REQ-012	Cobblestone Avoidance	Scenario 2.1	**New**	UC7
D.A.3	Speed Range	§2.4.1	**Refined**	–
H3	IMU/Accelerometer	§3.2	**Enhanced**	–
SP-1	Bandpass Filter	–	**New**	–
SP-2	Quaternion Tracking	–	**New**	–

A.9 Physical Reference Data (New)

The following empirical data from SimRa research informs the detection algorithm parameters:

Table 20: Bike Pothole Physical Characteristics (SimRa Berlin Dataset)

Parameter	Normal Riding	Pothole Impact
Z-axis acceleration	0.2–0.8 G	1.5–4.0 G
Jerk (rate of change)	< 2 G/s	4–10 G/s
Impact frequency	–	5–15 Hz
Impact duration	–	50–200 ms

A.10 Deprecation Notices

Table 21: Deprecated Specifications

v1.0 Specification	Status	Replacement
Fixed threshold $G_z > 2.0g$ (UC4)	Deprecated	Adaptive threshold with base 1.8G (R3.1)
Speed range 5–35 km/h (D.A.3)	Deprecated	Speed range 4–50 km/h (D.A.3 revised)
Binary confirm/reject (UC5)	Superseded	Community voting system (R4 enhanced)

A.11 Conclusion

RASD v2.0 represents a significant evolution of the original specification based on:

1. **Field Testing**: 50+ cyclists provided feedback over 500+ hours of recorded rides
2. **Research Integration**: SimRa Berlin dataset (10,000+ labeled events) informed algorithm parameters

3. **User Feedback**: New features (background tracking, weather alerts, water fountains) address real user needs
4. **False Positive Reduction**: ML-based detection reduces false positives by approximately 40% compared to threshold-only detection

All changes maintain backward compatibility with the original system architecture while significantly improving detection accuracy and user experience.

— End of Requirements Evolution Appendix —

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