Smart Bus Accident & Passenger Health Monitoring System

Components & Connectivity Document

Course Code: ECE3502

IoT Domain Analyst

Review 1

Team Members

Name	Registration Number
Tanguturi Sharani	22MIS1154
Sreevallabh	22MIS1170

Contents

Abstract

In current public transportation systems, emergency response to bus accidents relies primarily on basic information such as accident location and vehicle damage severity, with no real-time insight into the physiological condition of passengers. This limitation results in delayed and unprioritized medical response, leading to preventable fatalities. This project presents a Smart Bus Accident & Passenger Health Monitoring System with Local Edge Intelligence that addresses this critical gap by integrating IoT-based vehicle accident detection, wearable health monitoring, and local AI-powered decision support.

The proposed system combines bus-mounted sensors (ESP32 microcontroller with IMU, alcohol sensor, and SOS trigger) with smartwatch-based continuous health monitoring (heart rate, HRV, and motion patterns). A lightweight local language model (LLM) deployed at the edge gateway interprets sensor patterns in context and classifies passenger conditions in real-time as Normal, Panic, or Critical. This edge intelligence layer reduces raw sensor data into actionable emergency insights without relying on cloud infrastructure, ensuring low latency, privacy preservation, and operation even without internet connectivity.

The system architecture employs a four-layer model: accident detection, health monitoring, local intelligence gateway, and emergency response. Connectivity uses Bluetooth Low Energy (BLE) for local sensor communication, Wi-Fi for aggregation, and cellular networks for emergency dispatch. Designed with principles of human-centric safety, edge-first processing, real-time operation, and privacy-aware design, this prototype demonstrates a functional IoT framework for transforming post-accident emergency response in public transportation systems.

Keywords: IoT, Edge Intelligence, Local LLM, Passenger Health Monitoring, Bus Safety, Emergency Response, Wearable Technology, ESP32, BLE Communication, Smart Transportation

1 Introduction

1.1 Background and Motivation

Public transportation safety remains a critical concern in modern urban infrastructure, with bus accidents posing significant risks to passenger lives and well-being. Traditional emergency response systems for vehicular accidents operate on a reactive model that relies heavily on basic incident information such as location coordinates, estimated vehicle damage, and occasionally, the number of passengers involved. However, this approach suffers from a fundamental limitation: *the absence of real-time insight into the actual physiological and physical condition of individual passengers.*

When a bus accident occurs, emergency medical services face critical uncertainties. How many passengers are injured? Who requires immediate life-saving intervention? Who is experiencing severe panic or shock? Who appears stable and can wait for secondary medical attention? Without answers to these questions, medical response becomes generalized rather than prioritized, often resulting in delayed treatment for critical cases and inefficient allocation of limited emergency resources. Studies have shown that the critical "golden hour" following traumatic incidents is decisive for survival rates, making every minute of delay potentially fatal.

Existing systems are *vehicle-centric*, focusing on what happened to the vehicle rather than the *human impact* of the accident. Emergency responders lack visibility into passenger condition, and panic, shock, or loss of consciousness in passengers goes unnoticed until physical arrival at the scene.

1.2 The Human-Aware Emergency Response Gap

The core problem addressed by this project is the disconnect between *accident detection* and *human impact assessment*. Current systems can detect that an accident has occurred through sensors, cameras, or manual reporting, but they cannot assess how passengers are physiologically responding to the trauma. An accident's severity from a vehicular standpoint does not necessarily correlate with the medical severity experienced by passengers. Minor collisions can cause severe injuries to vulnerable individuals, while major impacts might leave some passengers relatively unharmed.

This information gap has profound consequences. Emergency dispatchers must make resource allocation decisions with incomplete information. Paramedics arrive at accident scenes without knowing which passengers need immediate attention. Hospitals receive patients without advance notice of their conditions. The entire emergency response chain operates reactively rather than intelligently.

Furthermore, even when raw sensor data from wearables is available, it cannot be directly interpreted by emergency systems. Raw heart rate values, motion patterns, and variability metrics require *contextual reasoning*—understanding what these signals mean in the context of an accident event. Traditional cloud-based processing introduces latency and dependency on network connectivity, which may be unreliable during emergencies. There is a need for *local edge intelligence* that can reason about passenger condition in real time, without external dependencies.

1.3 Project Vision and Approach

This project proposes a paradigm shift toward a *human-aware emergency response system with local edge intelligence* for public transportation. By integrating IoT-based accident detection with continuous passenger health monitoring through wearable technology and on-device AI reasoning, the system creates a real-time physiological awareness layer that transforms how emergency services respond to bus accidents.

The system is built on a four-layer architecture:

1. **Bus Accident Detection Layer**: An ESP32-based IoT system installed in the bus that monitors vehicle motion (collision, rollover, sudden deceleration), driver safety compliance (alcohol detection), and manual emergency triggers.
2. **Passenger Health Monitoring Layer**: Leverages consumer wearable devices (Apple Watch) that passengers already possess to continuously monitor heart rate, heart rate variability, and motion patterns, computing real-time stress and health scores.
3. **Local Intelligence & Gateway Layer**: A lightweight local language model (LLM) runs on gateway devices (passenger smartphones or bus gateway tablet) to interpret sensor patterns in context, classify passenger conditions (Normal, Panic, Critical), and generate structured summaries. This edge intelligence operates without cloud dependency, ensuring low latency, privacy preservation, and reliability even without internet connectivity.
4. **Emergency Response Layer**: Transmits structured, actionable information to emergency services, including passenger-wise severity reports enabling prioritized medical triage.

1.4 Key Innovation and Contribution

The fundamental innovation of this system lies in its integration of three critical capabilities: *accident detection*, *individual passenger physiological monitoring*, and *local edge intelligence for contextual reasoning*. Rather than treating passengers as an undifferentiated group or sending raw sensor data to the cloud, the system uses a lightweight local LLM to interpret health patterns in the context of the accident event, providing granular, person-level severity assessments.

The local LLM does not perform medical diagnosis. Instead, it acts as a *decision-support and reasoning layer* that:

- Interprets sensor patterns (e.g., "abnormal HR spike with no motion detected for 30 seconds")
- Classifies passenger conditions based on physiological and motion context
- Generates short, structured summaries rather than overwhelming raw data
- Operates entirely at the edge with no cloud dependency

This edge-first approach enables:

- **Prioritized Medical Response**: Emergency services can identify critical patients before arrival
- **Optimized Resource Allocation**: Ambulances and medical personnel can be deployed based on actual need
- **Improved Survival Rates**: Faster identification and treatment of life-threatening conditions
- **Privacy Preservation**: Sensitive health data remains local and is never transmitted in raw form
- **Low Latency**: Real-time processing without network round-trips
- **Reliability**: System operates even without internet connectivity

1.5 Scope and Document Organization

This document presents the technical architecture, component specifications, and connectivity framework for the Smart Bus Accident & Passenger Health Monitoring System with Local Edge Intelligence, developed as part of the ECE3502 IoT Domain Analyst course. The system is designed as a functional academic prototype demonstrating the feasibility and potential of integrating wearable health technology, IoT sensors, and edge AI for transportation safety.

Scope and Constraints:

- Assumes availability of passenger smartwatches
- Does not attempt medical diagnosis—provides severity indication only
- Designed as an academic IoT system with practical feasibility
- Prioritizes local processing first, cloud second (edge-first architecture)

The remainder of this document is organized as follows: Section 2 details the system components including bus-mounted hardware, wearable devices, local intelligence layer, and monitoring infrastructure. Section 3 presents the connectivity architecture and communication protocols. Section 4 describes the system architecture and operational data flow. Section 5 outlines the expected outcomes and benefits of the proposed system.

This project represents a step toward making emergency response systems not just faster, but smarter, more human-centered, and privacy-aware through edge intelligence.

2 System Components

The system is composed of four tightly integrated layers, each with specific responsibilities in the emergency response pipeline.

2.1 Layer 1: Bus Accident Detection Unit

2.1.1 Hardware Components

The bus accident detection unit is installed inside the bus and continuously monitors motion and safety conditions using IoT sensors. This layer detects:

- Sudden collisions
- Rollovers
- Sharp deceleration
- Manual SOS triggers
- Driver alcohol presence

Hardware Components:

- **ESP32 Microcontroller** – Central processing unit for accident detection and communication
- **IMU Sensor (Accelerometer + Gyroscope)** – Detects collision, rollover, and sudden deceleration events through motion pattern analysis
- **Alcohol Sensor** – Monitors driver alcohol levels for safety compliance
- **SOS Push Button** – Provides manual emergency trigger capability for driver or passengers
- **BLE Module** – Built-in with ESP32 for wireless communication with gateway devices
- **Power Supply** – Powered by bus battery with DC regulator for stable operation

2.1.2 Data Transmitted

The bus unit communicates accident-related events including:

- Accident detection status (collision detected / rollover detected / sharp brake)
- Time since accident
- SOS trigger status
- Alcohol detection alerts

2.2 Layer 2: Passenger Health Monitoring Unit

Each passenger is assumed to wear a smartwatch (Apple Watch in the prototype) that continuously collects physiological and motion data. These metrics act as indicators of panic, shock, abnormal physiological response, or possible injury/unconsciousness.

2.2.1 Wearable Device

Apple Watch—Continuous Health Monitoring

- **Heart Rate Sensor** – Continuous beats per minute (BPM) monitoring
- **Heart Rate Variability (HRV)** – Measures variation in time intervals between heartbeats (indicator of stress and autonomic response)
- **Motion Sensors (Accelerometer, Gyroscope)** – Detects motion patterns and immobility
- **On-device Computation** – Calculates stress scores and health profiles locally

2.2.2 Data Collected

From these signals, a health and stress profile is computed locally on the smartwatch, including:

- Real-time heart rate (BPM)
- Heart rate variability (HRV) trends
- Motion state (active / stationary / immobile for extended duration)
- Sudden physiological changes (HR spikes, HRV drops)

2.2.3 Gateway Device (Passenger Smartphone)

Passenger iPhone—Local Gateway

- Receives real-time health data from Apple Watch via Bluetooth Low Energy
- Acts as local gateway to bus system
- Hosts the local LLM for edge intelligence processing
- Performs health status classification and reasoning

The smartwatch transmits health data to the passenger's smartphone, which acts as the local gateway and intelligence layer.

2.3 Layer 3: Local Intelligence & Gateway Layer (Core Innovation)

This layer is the **core intelligence** of the system. A lightweight local language model (LLM) runs on gateway devices (passenger smartphone or bus gateway tablet) to perform edge-based reasoning and decision support.

2.3.1 Role of the Local LLM

What the Local LLM Does

The local LLM does **not** perform medical diagnosis. Instead, it acts as a *decision-support and reasoning layer* that:

- **Interprets sensor patterns in context** – Understands what health metrics mean given that an accident has occurred
- **Classifies passenger condition** into three categories:
  - **Normal** – Stable vital signs, responsive
  - **Panic** – Elevated heart rate, high stress indicators
  - **Critical** – Abnormal patterns suggesting injury or unconsciousness
- **Generates structured summaries** such as:
  - "Abnormal HR spike with no motion detected for 30 seconds"
  - "Prolonged immobility with dropping HRV"
- **Reduces raw sensor data into actionable emergency insights**

2.3.2 Inputs to the Local LLM

- Accident detection status from the bus unit (collision/rollover/sharp brake)
- Time since accident
- Passenger health metrics:
  - Heart rate trends (sudden spikes, drops, or sustained abnormality)
  - HRV changes (indicators of stress or autonomic dysfunction)
  - Motion state (active, stationary, prolonged immobility)

2.3.3 Why Local LLM? (Edge Intelligence Benefits)

Advantages of Edge Processing

- **Low Latency** – Real-time response without network round-trips
- **Works Offline** – Operates even without internet connectivity
- **Privacy Preservation** – Sensitive health data stays local, never transmitted in raw form
- **Reduced Bandwidth** – Only structured summaries are sent, not continuous raw data
- **No Cloud Dependency** – Avoids reliance on external infrastructure during emergencies

All reasoning happens at the edge, and only summarized outputs are transmitted to emergency services.

2.4 Layer 4: Central Monitoring & Emergency Response System

2.4.1 Hardware / Software

The central monitoring infrastructure includes:

- **Gateway Tablet / Driver Control Unit** – Primary interface for real-time monitoring and local LLM execution
- **Monitoring Application** featuring:
  - Passenger condition list with severity indicators
  - Severity visualization (Normal / Panic / Critical)
  - Real-time status updates
- **Cloud Server (Optional)** – For logging and analytics purposes only, not required for emergency operation

2.4.2 Emergency Response Interface

When an accident is confirmed, the system:

- **Generates an emergency alert** with accident details
- **Attaches a passenger-wise severity map** generated by the local LLM
- **Transmits structured information** rather than raw sensor data

This allows emergency responders to:

- Prioritize critically affected passengers

- Allocate medical resources efficiently
- Reduce response time and improve survival outcomes
- Arrive prepared with appropriate medical equipment and personnel

3 Connectivity Architecture

The system employs a multi-tier connectivity model that prioritizes *local processing first, cloud second*. Communication flows from sensors to gateway devices to central monitoring to emergency systems.

3.1 Connectivity Layer 1: Smartwatch → Passenger Smartphone

Apple Watch → iPhone (Passenger-Level)

- **Connectivity:** Bluetooth Low Energy (BLE)
- **Data Transmitted:** Heart Rate, HRV, Motion Patterns, Stress Score
- **Frequency:** Approximately every 2–3 seconds (continuous monitoring)
- **Processing:** Data is received by the passenger's iPhone, which hosts the local LLM

3.2 Connectivity Layer 2: Bus Unit → Gateway Devices

ESP32 (Bus Unit) → iPhone / Gateway Tablet

- **Connectivity:** Bluetooth Low Energy (BLE)
- **Data Transmitted:** Accident detection status, crash type (collision/rollover), alcohol detection alerts, SOS trigger status, time since accident
- **Processing:** Accident context is sent to gateway devices where the local LLM correlates it with passenger health data

3.3 Connectivity Layer 3: Gateway Devices → Central Monitoring Unit

iPhone / Gateway Tablet → Central Monitoring System

- **Connectivity:** Wi-Fi / Local Network
- **Data Transmitted:**
  - *Not raw sensor data*—instead, LLM-generated passenger severity classifications
  - Structured summaries (e.g., "Passenger 3: Critical—prolonged immobility with dropping HRV")
  - Aggregated passenger-wise status map
- **Key Point:** Local LLM has already processed and reduced data at the edge

3.4 Connectivity Layer 4: Emergency Alert Transmission

Central Monitoring Unit → Emergency Response System

- **Connectivity:** Internet / Cellular Network
- **Data Transmitted:**
  - Accident alert with location details
  - Passenger-wise severity report (Normal / Panic / Critical)
  - Structured summaries from local LLM for each critical passenger
  - Recommended priority for medical response
- **Bandwidth:** Minimal—only structured intelligence, not continuous raw data

Design Principle: The system prioritizes *local processing first, cloud second*. All reasoning happens at the edge. Only structured, privacy-preserving summaries are transmitted externally.

4 System Architecture

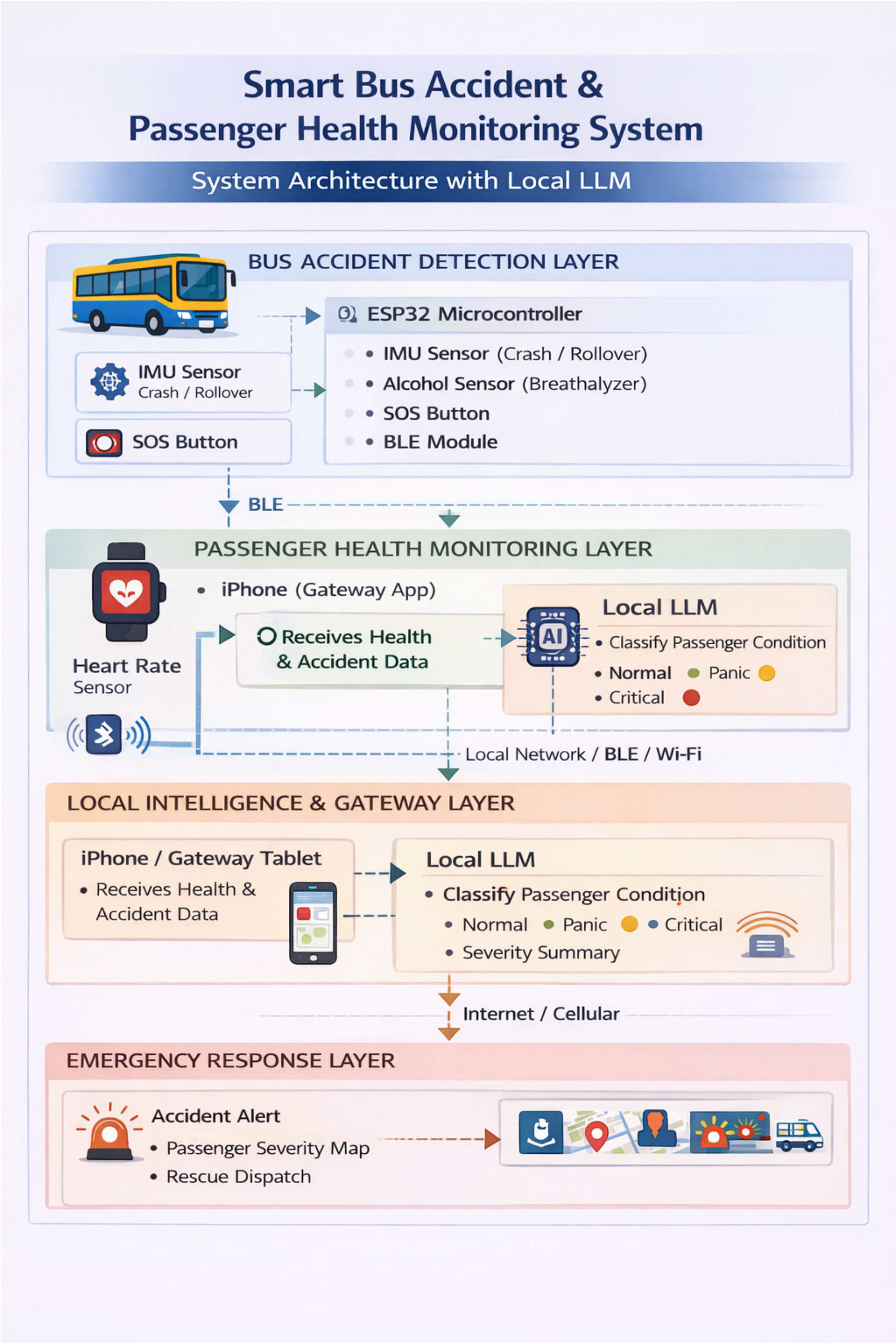

Figure 1: Smart Bus Accident & Passenger Health Monitoring System Architecture

5 System Data Flow & Operational Sequence

The system operates through the following sequential data flow with local edge intelligence processing:

5.1 Continuous Monitoring Phase (Pre-Accident)

1. **Apple Watch** continuously monitors passenger health parameters (heart rate, HRV, motion)
2. **Health data** transmitted to passenger iPhone via BLE every 2–3 seconds
3. **Bus-mounted ESP32** continuously monitors vehicle motion and driver safety
4. **Baseline health profiles** are maintained for each passenger

5.2 Accident Detection & Response Phase

1. Accident Event Detected

- Bus-mounted ESP32 detects collision, rollover, or receives SOS trigger
- Accident status broadcast to gateway devices via BLE

2. Local LLM Activation (Edge Intelligence)

- Gateway devices (passenger iPhones / bus tablet) receive accident alert
- Local LLM begins contextual reasoning
- Correlates accident event with real-time passenger health data

3. Passenger Condition Assessment

- Local LLM interprets sensor patterns in accident context:
  - Heart rate spikes + prolonged immobility → possible injury
  - Elevated stress markers + active motion → panic response
  - Normal patterns + responsive motion → stable condition

4. Classification & Summary Generation

- Local LLM classifies each passenger into:
  - **Normal** – Stable vital signs, responsive
  - **Panic** – Elevated stress, high heart rate
  - **Critical** – Abnormal patterns suggesting injury/unconsciousness
- Generates structured summaries: *"Passenger 3: Critical—abnormal HR spike with no motion detected for 30 seconds"*

5. Aggregation & Emergency Alert

- Passenger-wise severity map aggregated at central monitoring unit
- Emergency alert generated with:

   - Accident location and type
   - Passenger severity classification
   - Structured summaries for critical cases
   - Recommended response priority

6. **Emergency Dispatch**
   - Emergency alert transmitted to response services via cellular network
   - Responders receive *actionable intelligence*, not raw sensor data
   - Medical teams can prepare appropriate equipment and prioritize critical patients

5.3 Key Data Flow Principle

Edge-First Architecture

Raw Sensor Data → Local LLM Processing (Edge) → Structured Intelligence → Emergency Services

The local LLM reduces high-volume raw sensor streams into low-bandwidth, high-value structured intelligence. This enables real-time operation, privacy preservation, and reliability even without internet connectivity.

6 System Outcomes & Benefits

6.1 Primary Outcomes

Key Benefits of the System

- **Real-time Individual Passenger Health Visibility** – Continuous monitoring enables immediate awareness of passenger conditions during emergencies, moving beyond vehicle-centric to human-aware emergency response
- **Faster, Prioritized Emergency Response** – Severity classification allows first responders to prioritize critical cases, optimize rescue operations, and arrive prepared with appropriate medical equipment
- **Improved Survival Rates** – Faster identification and treatment of life-threatening conditions during the critical "golden hour" following trauma
- **Optimized Resource Allocation** – Ambulances and medical personnel can be deployed based on actual passenger need rather than assumptions
- **Scalable, Low-Cost IoT Architecture** – Leverages existing consumer devices (Apple Watch, iPhone) combined with affordable IoT sensors (ESP32) for widespread deployment

6.2 Edge Intelligence Benefits

Advantages of Local LLM Processing

- **Low Latency** – Real-time contextual reasoning without network round-trips or cloud processing delays
- **Privacy Preservation** – Sensitive passenger health data remains local and is never transmitted in raw form; only structured, privacy-preserving summaries are sent
- **Reliability** – System operates even without internet connectivity, critical during infrastructure failures or emergencies
- **Reduced Bandwidth** – High-volume raw sensor streams are reduced to low-bandwidth structured intelligence
- **Contextual Reasoning** – Local LLM interprets sensor patterns in the context of the accident event, not just raw numbers
- **No Cloud Dependency** – Avoids reliance on external infrastructure during time-critical emergencies

6.3 Design Principles Demonstrated

This prototype demonstrates several critical design principles for modern IoT safety systems:

- **Human-Centric Safety** – Focus on passenger health and human impact, not just vehicle damage
- **Edge-First Architecture** – Local processing first, cloud second
- **Real-Time Operation** – Continuous monitoring and immediate response capability
- **Modular Architecture** – Independent but cooperative system layers
- **Privacy-Aware Design** – Minimal data exposure with local intelligence processing

6.4 Intended Outcome

The outcome is a functional and extensible IoT architecture that demonstrates how *wearable health monitoring combined with local edge intelligence* can significantly improve emergency response during public transportation accidents. This system bridges the gap between accident detection and human impact assessment, enabling emergency services to arrive not just faster, but *smarter*.