Complex Engineering Problem

Stochastic Processes (SE-410)

Group : A-02

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1. Introduction

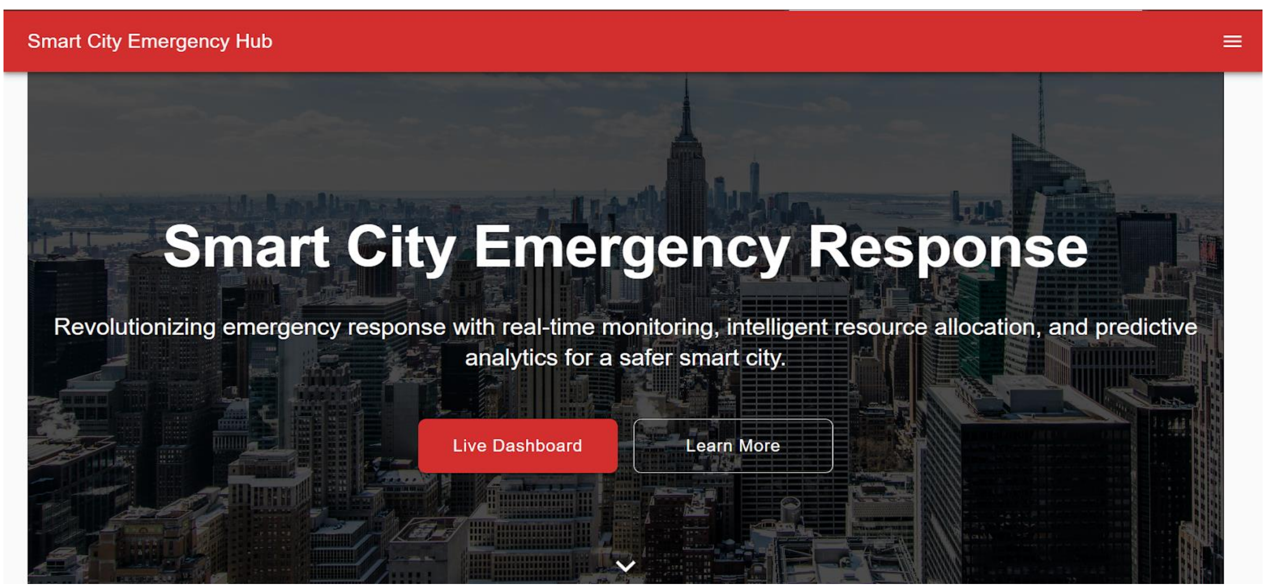
The Smart City Emergency Response System is an innovative project designed to transform emergency management through real-time data processing and advanced stochastic modeling. The system enables organizations to monitor and manage emergency responses by providing live updates every 5 seconds on incidents such as medical, fire, and police emergencies. It optimally allocates limited emergency units using queuing theory, forecasts future emergency patterns using Markov chain models, and explicitly simulates incident arrivals with the Poisson process. By integrating these three approaches, the system not only handles the current emergency load effectively but also anticipates future trends enhancing both immediate response and long-term strategic decision-making.

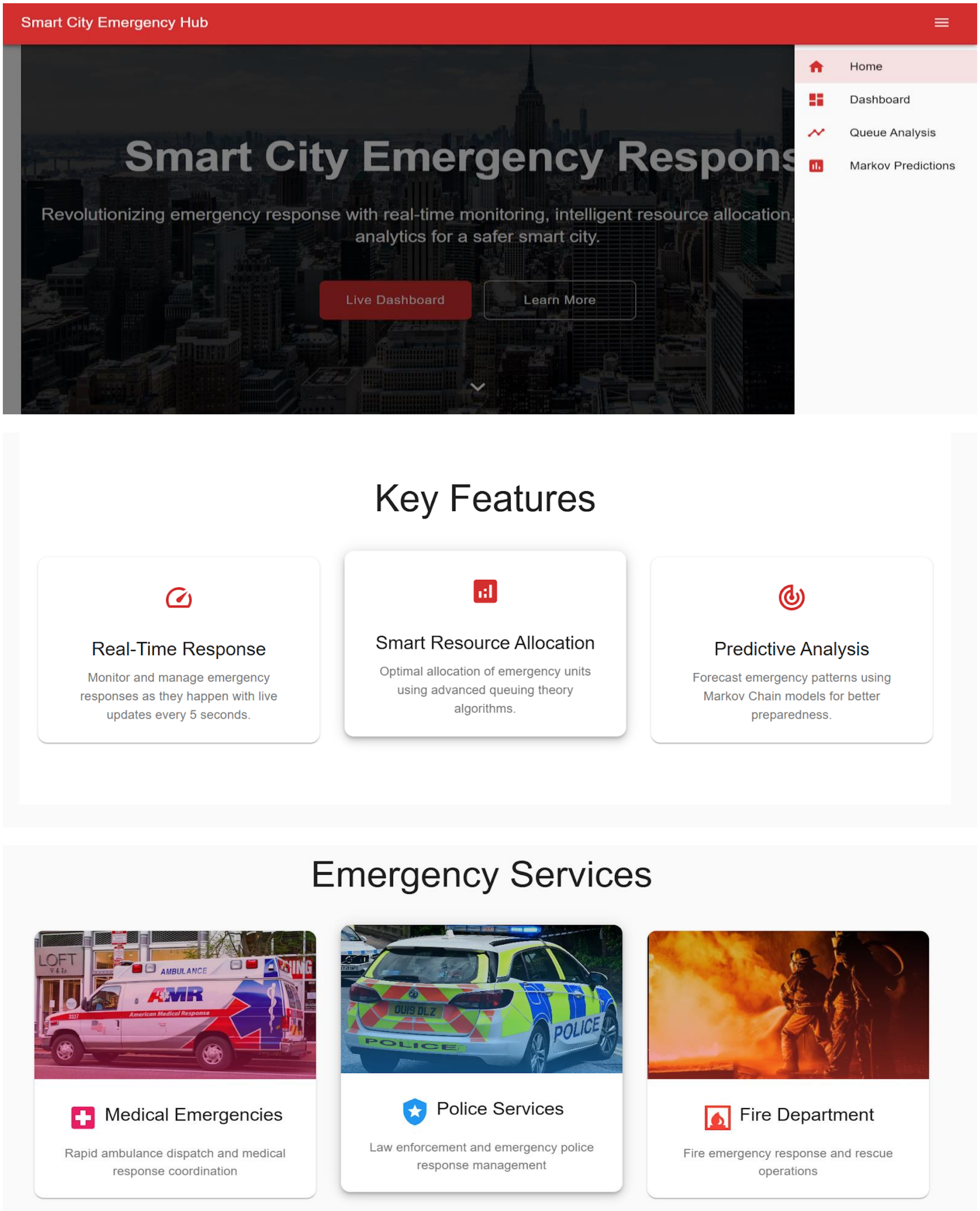
2. Detailed Functionality and Visualizations

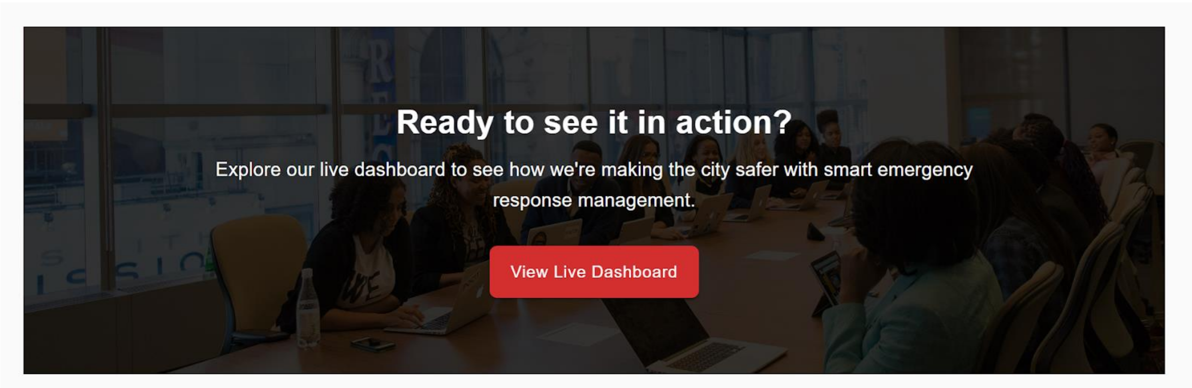
2.1. Homepage

Overview:

The Homepage introduces the system with a captivating hero section, animated elements, and clear navigation cues. It provides a high-level summary of the system's core functionalities: real-time response, smart resource allocation via queuing theory, and predictive analysis using Markov chain models.




Smart City Emergency Hub
Home
Dashboard
Queue Analysis
Markov Predictions
Smart City Emergency Respons
Revolutionizing emergency response with real-time monitoring, intelligent resource allocation,
analytics for a safer smart city.
Live Dashboard
Learn More
Key Features
Real-Time Response
Monitor and manage emergency responses as they happen with live updates every 5 seconds.
Smart Resource Allocation
Optimal allocation of emergency units using advanced queuing theory algorithms.
Predictive Analysis
Forecast emergency patterns using Markov Chain models for better preparedness.
Emergency Services
Medical Emergencies
Rapid ambulance dispatch and medical response coordination
Police Services
Law enforcement and emergency police response management
Fire Department
Fire emergency response and rescue operations



2.2 Dashboard

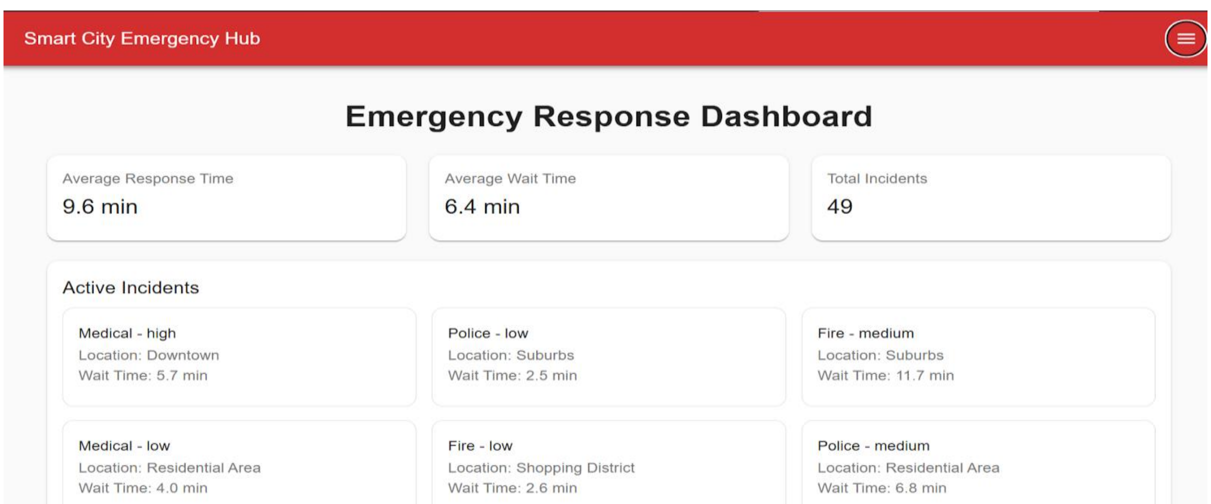
Functionality:

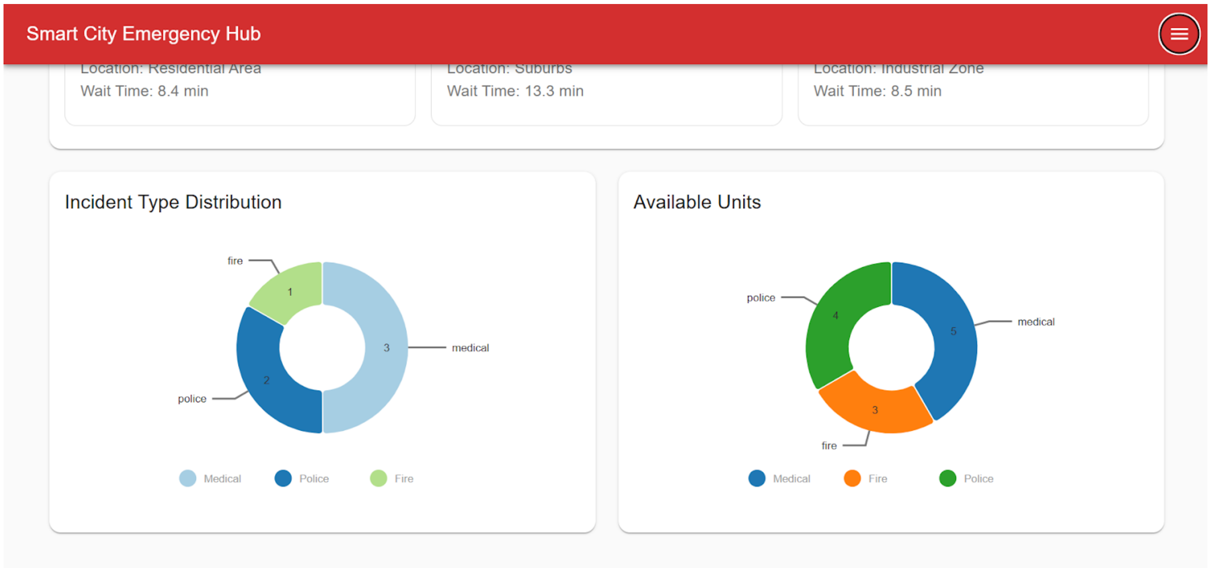
The Dashboard aggregates and displays key real-time metrics:

1. **Average Response Time, Average Wait Time, Total Incidents:** Computed by the backend simulation.
2. **Incident Type Distribution:** A pie chart visualizes the spread of active incidents (medical, fire, police)
3. **Available Units:** A separate pie chart shows the current availability of emergency units.

Stochastic Application:

This page reflects the outcomes of the queuing model, demonstrating how random incident arrivals and dynamic resource allocation affect overall performance.





2.3 Queue Analysis Page

Functionality:

The Queue Analysis page provides an in-depth view of service-specific performance metrics through responsive charts:

1. **Service Metrics Comparison (Bar Chart):** Compares wait time, service time, queue length, and utilization across medical, fire, and police services.
2. **Queue Length Over Time (Line Chart):** Displays how queue lengths for each service evolve over recent simulation steps.
3. **Incident Volume by Service Type (Bar Chart):** Shows the total number of incidents handled per service, indicating demand.
4. **Wait Time vs Queue Length (Heatmap):** Visualizes the relationship between how long incidents wait and the number of incidents in the queue.

Stochastic Application:

Based on queuing theory, this page uses simulated incident arrivals and service metrics to verify monitor system performance, identify bottlenecks, and analyze how real-time demand affects waiting times and resource allocation.

Smart City Emergency Hub

Queue Analysis

Average Wait Time	Average Service Time	System Utilization	Total Queue Length
5.4 min	13.3 min	67.0%	8

Medical

Wait Time	Service Time
2.9 min	16.2 min
Queue Length	**Utilization**
2	70.0%

Fire

Wait Time	Service Time
6.4 min	10.9 min
Queue Length	**Utilization**
5	74.0%

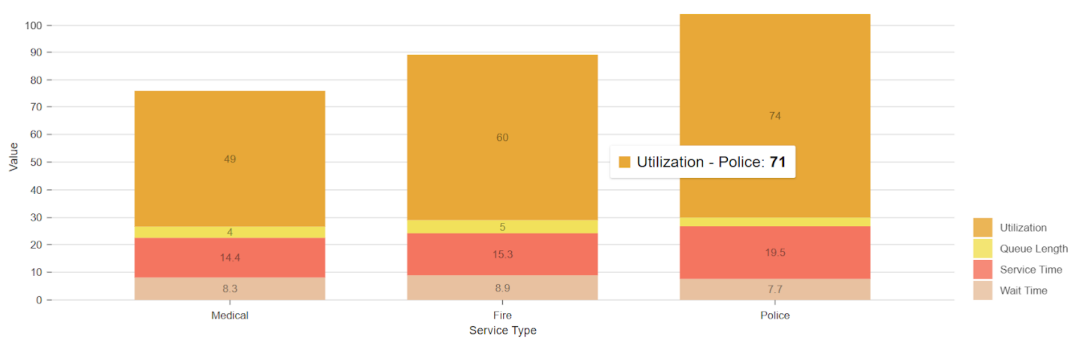
Police

Wait Time	Service Time
6.8 min	12.8 min
Queue Length	**Utilization**
1	56.0%

Service Metrics Comparison

Smart City Emergency Hub

Service Metrics Comparison



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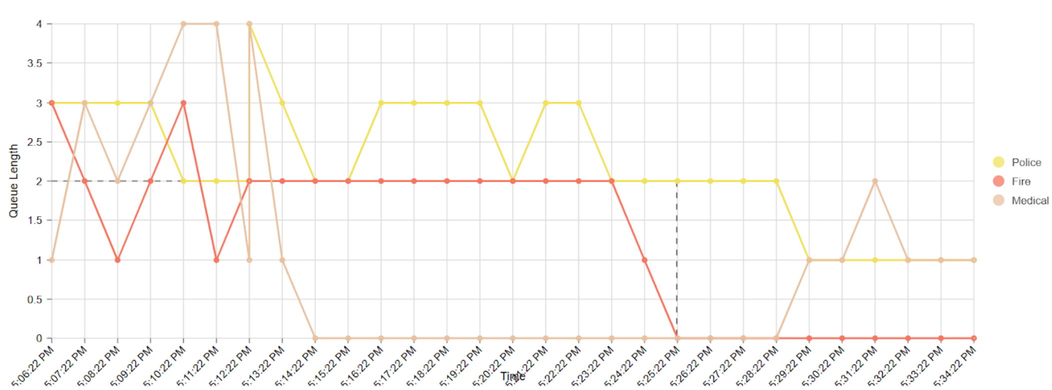
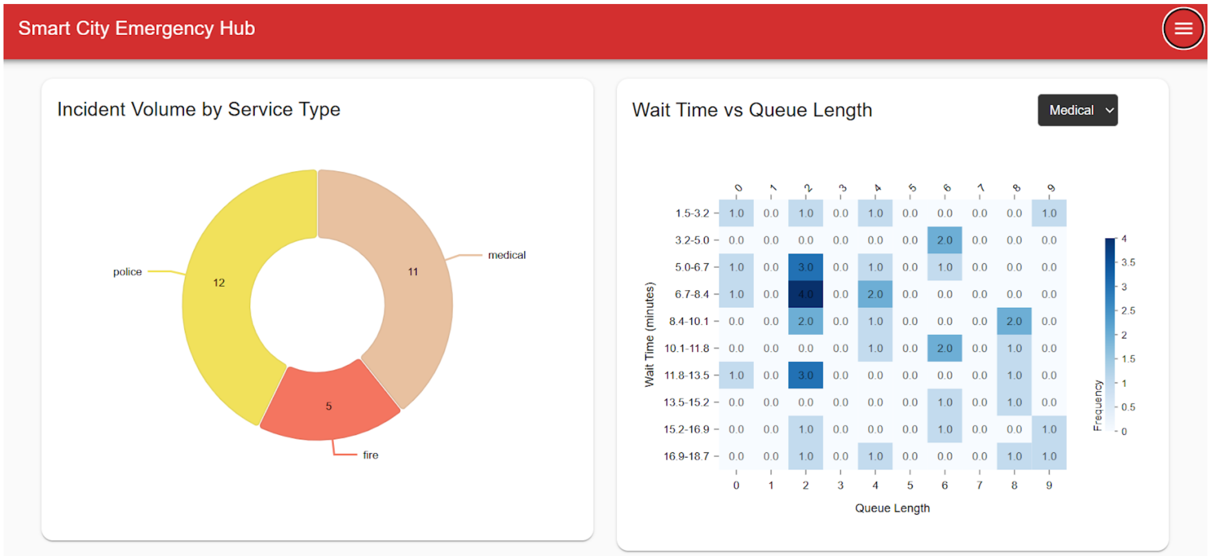
Queue Length Over Time





2.4 Markov Predictions Page

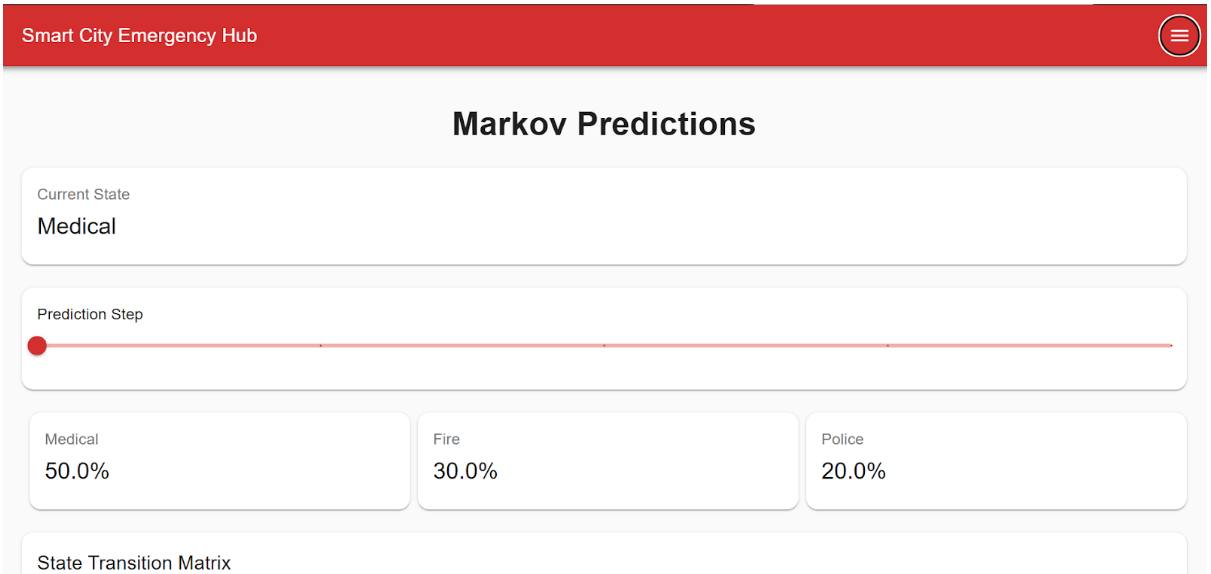
Functionality:

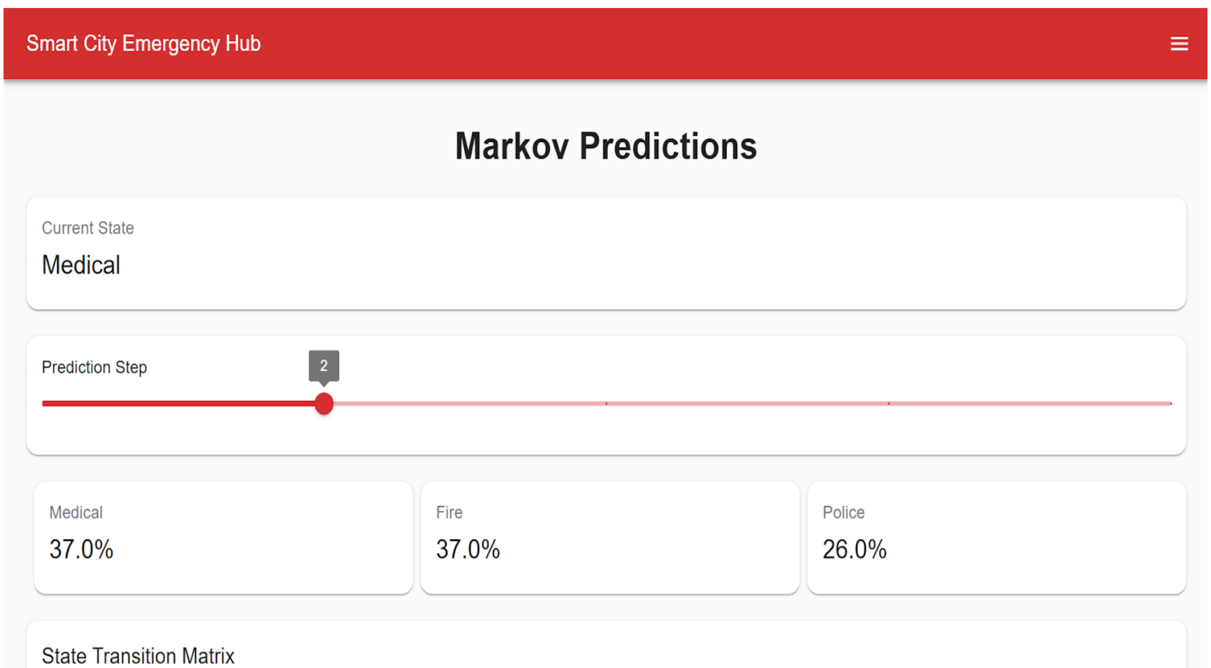
The Markov Predictions page forecasts future emergency states:

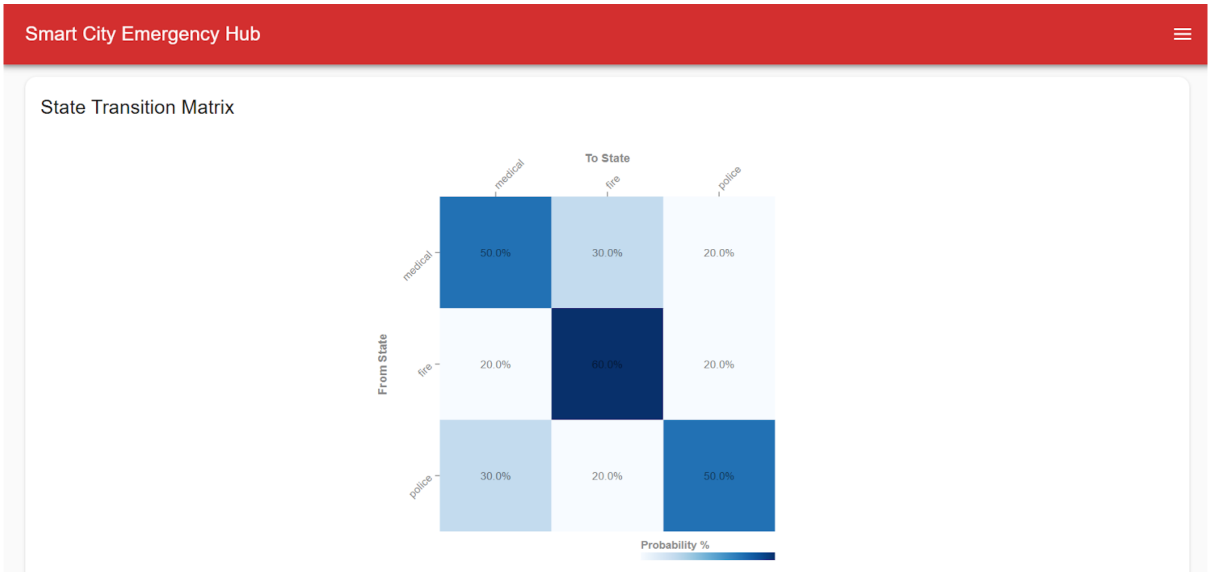
1. **Prediction Step Selector:** A slider allows users to select the prediction step.
2. **Prediction Cards:** Display the probability for each state (medical, fire, police) at the chosen step.
3. **State Transition Matrix (Heatmap):** Illustrates the transition matrix, showing the likelihood of the system transitioning between states.
4. **Probability Over Time (Line Chart):** Shows how the likelihood of each emergency type evolves over multiple prediction steps.

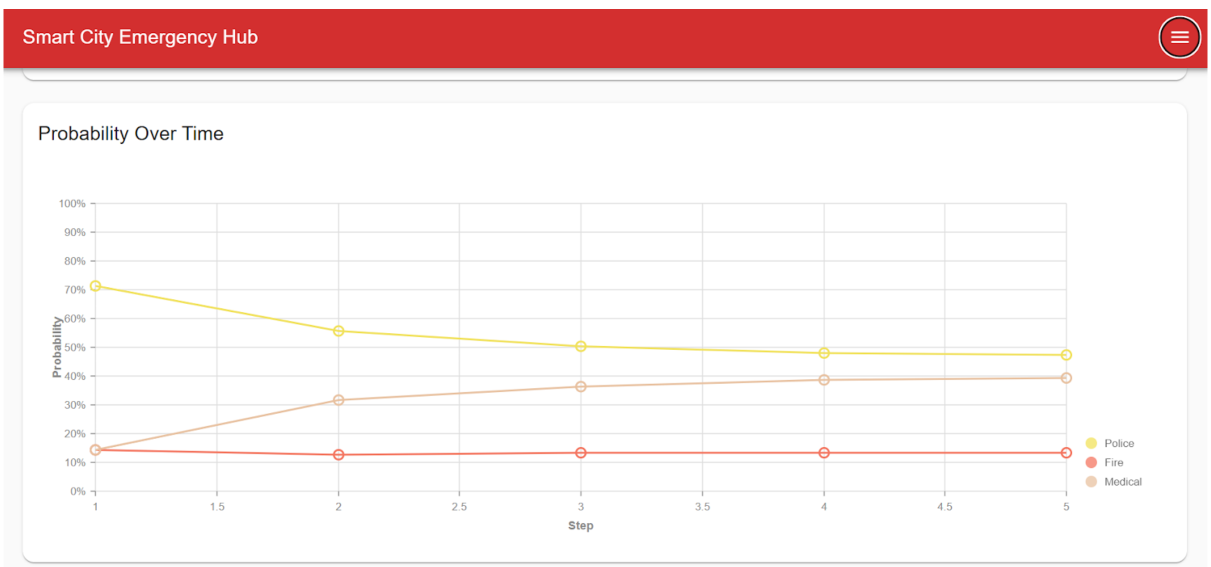
Stochastic Application:

Utilizing a Markov chain model based on the memoryless property, the system iteratively computes future state probabilities. Each prediction is derived from the current state using a fixed transition matrix, providing a forward-looking analysis of emergency patterns.


Smart City Emergency Hub
Markov Predictions
Current State
Medical
Prediction Step
Medical
50.0%
Fire
30.0%
Police
20.0%
State Transition Matrix


Smart City Emergency Hub
Markov Predictions
Current State
Medical
Prediction Step
2
Medical
37.0%
Fire
37.0%
Police
26.0%
State Transition Matrix





2.5 <u>Poisson Simulation Page</u>

Functionality:

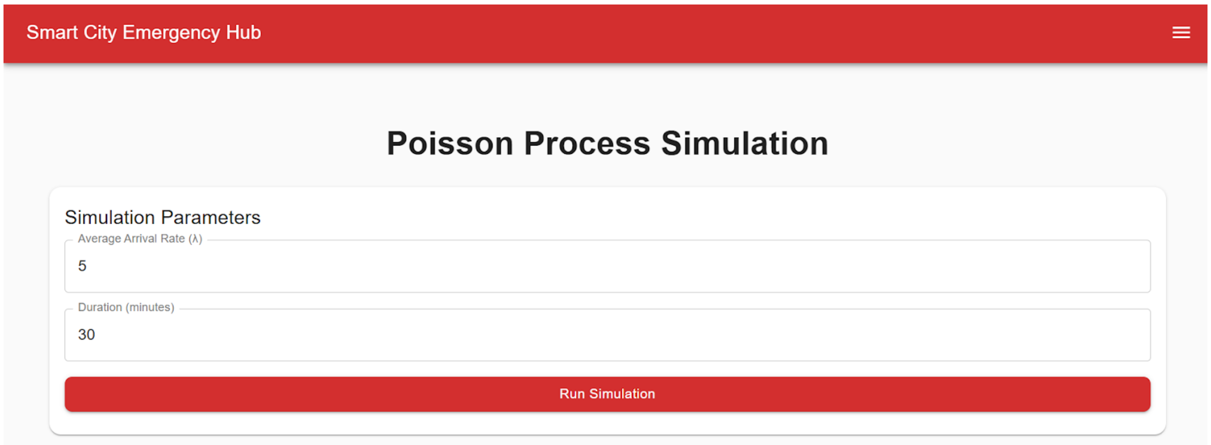
The Poisson Simulation page models incident arrivals using a Poisson process.

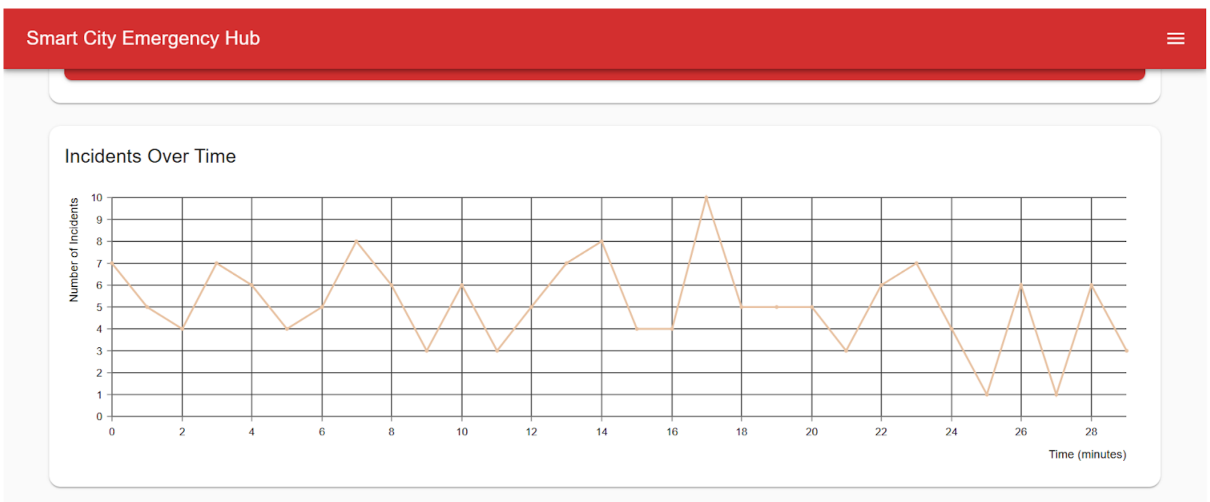
1. **Simulation Parameters Input:** Users input arrival rate (λ) and duration (minutes) to trigger a new simulation.
2. **Incidents Over Time (Line Chart):** Visualizes the number of incidents arriving at each minute across the simulation period.
3. **Inter-arrival Time Distribution:** Displays a histogram of time gaps between arrivals, illustrating exponential distribution.

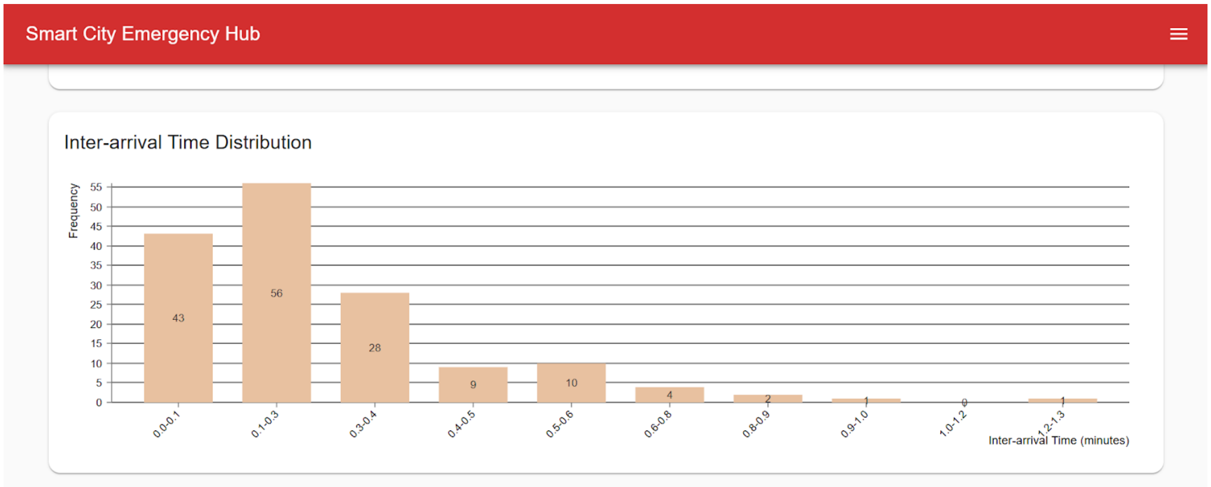
4. **Poisson vs. Random Arrivals Chart:** Compares incidents generated via Poisson distribution and uniform random process, highlighting differences in mean and variance.

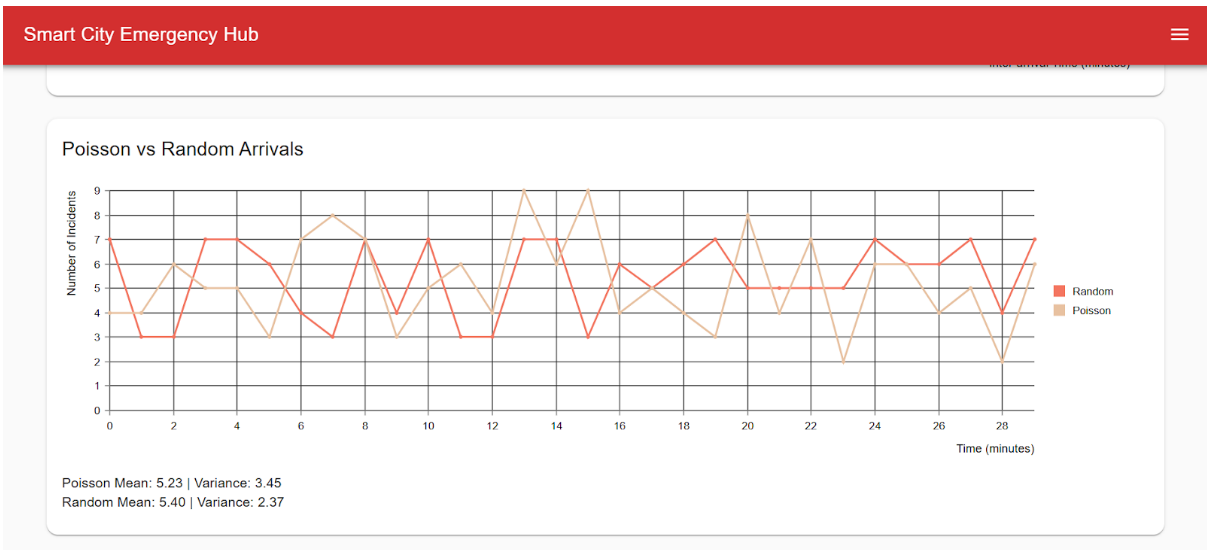
Stochastic Application:

Applies the Poisson process to simulate real-world emergency incident arrivals, demonstrating variability over time and validating statistical consistency compared to random distributions.









3. Stochastic Concepts: Why Use Both Queuing Theory and Markov Chains?

Queuing Theory:

- **Purpose:** Simulates the real-time arrival of emergency incidents and the allocation of resources.
- **Key Metrics:** Average wait time, service time, queue length, and unit utilization.
- **Application:** Optimizes immediate dispatch and management of emergency units.

Markov Chains:

- **Purpose:** Forecasts future emergency states by applying a transition matrix to the current state.

- **Key Concept:** Utilizes the memoryless property, where each prediction is based solely on the current state.
- **Application:** Provides a proactive outlook for long-term planning.

Poisson Process:

- **Purpose:** Explicitly simulates the random arrival of emergency incidents.
- **Key Feature:** Characterized by a constant average arrival rate (λ) and exponentially distributed inter-arrival times.
- **Application:** Enhances the accuracy of the queuing model by ensuring that the simulation of incident arrivals mirrors real-world conditions.

Combined Rationale:

Integrating all three stochastic concepts allows the system to manage immediate operational loads (via queuing theory), predict future trends (through Markov chains), and explicitly simulate realistic incident arrivals (using the Poisson process). This comprehensive approach results in a robust, adaptive framework capable of both efficient real-time management and strategic foresight.

4. Conclusion

The Smart City Emergency Response System is a testament to the transformative power of stochastic modeling in modern emergency management. By integrating **queuing theory**, **Markov chains**, and a **Poisson process simulation**, the system achieves both real-time optimization and predictive foresight. Queuing theory governs the live resource allocation across emergency services, while the Markov model leverages its memoryless property to forecast future state transitions and incident distributions. The newly added Poisson simulation further strengthens the project by modeling the natural randomness of incident arrivals—highlighting how emergency events follow a probabilistic pattern over time. Together, these models create a comprehensive, adaptive framework that enhances operational efficiency and situational awareness. This theoretical depth is brought to life through a seamless FastAPI backend and a dynamic React/Next.js frontend, delivering powerful real-time insights through engaging visualizations and interactive dashboards.