Project-Report of Sustainable Systems Engineering: Analysis of ACTM Traffic Model with ALINEA Control

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1 Introduction

This study simulates traffic flow using a Cell Transmission Model (CTM) for a freeway segment discretized into 20 sections (links) of 0.5 km each. It applies the ALINEA ramp metering control strategy. We analyze the system's behavior across three distinct traffic demand scenarios to assess the control's effectiveness in managing congestion.

2 Traffic Scenarios and Analysis

2.1 Standard Traffic Pattern

This scenario simulates an initial period of high demand followed by a drop to a sustained lower demand (specifically, 100 veh/hr for ramps on links 4 and 9, and 50 veh/hr for the ramp on link 11 in the off-peak period, as per the simulation setup), testing the system's ability to manage congestion formation and subsequent recovery.

2.1.1 Analysis of Standard Traffic Pattern Results

- **Ramp Traffic Flow (Links 4, 9, 11):** In the uncontrolled case, ramp flow directly mirrored demand. However, the ALINEA controller actively metered this flow during high demand to prevent mainline congestion, then adapted by allowing more flow as demand dropped.

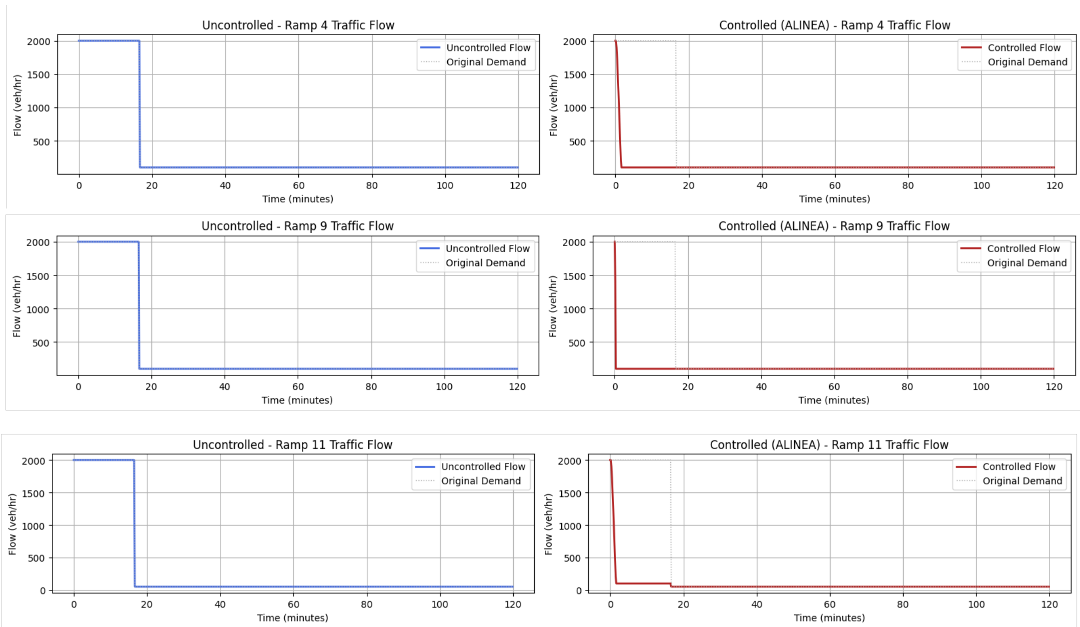

Figure 1: Ramp traffic flow along Links 4, 9, and 11 for the Standard Traffic Pattern.

- **Downstream Density (Links 5, 10, 12):** Uncontrolled densities surged significantly during peak demand, indicating severe and lingering congestion. In contrast, ALINEA consistently maintained downstream densities much closer to the target (60 veh/km), a value typically chosen to be near the critical density for optimal flow, effectively preventing severe congestion and facilitating quicker recovery.

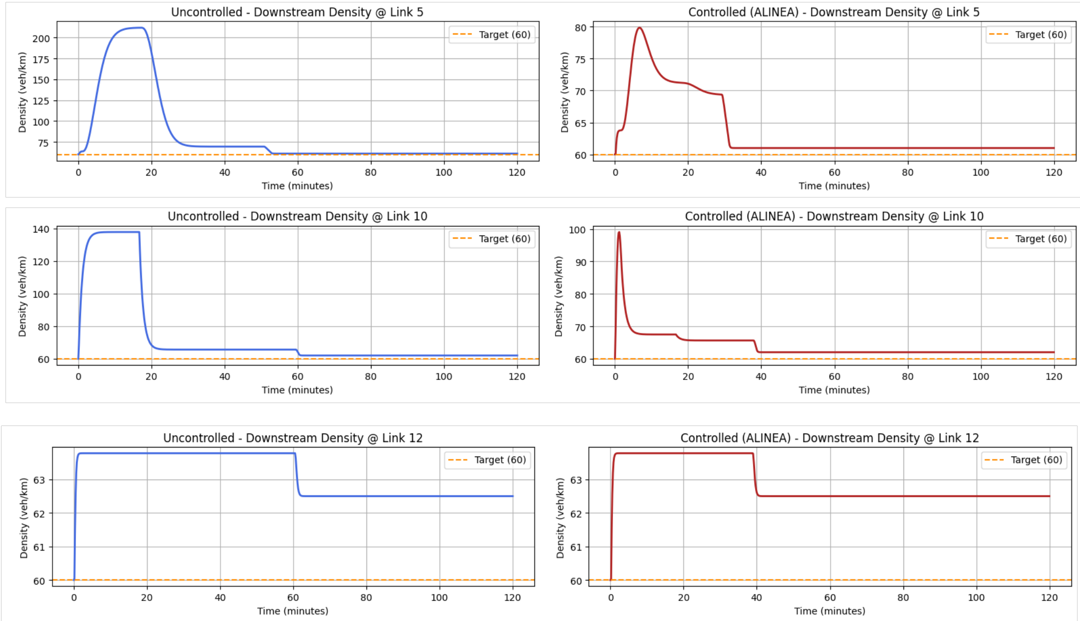

Figure 2: Downstream Density along Links 5, 10, and 12 for the Standard Traffic Pattern.

- **Downstream Flow (Links 5, 10, 12):** While uncontrolled flow suffered capacity drops due to congestion, ALINEA, by mitigating density buildup, ensured higher and more stable mainline throughput, allowing traffic to flow more efficiently.

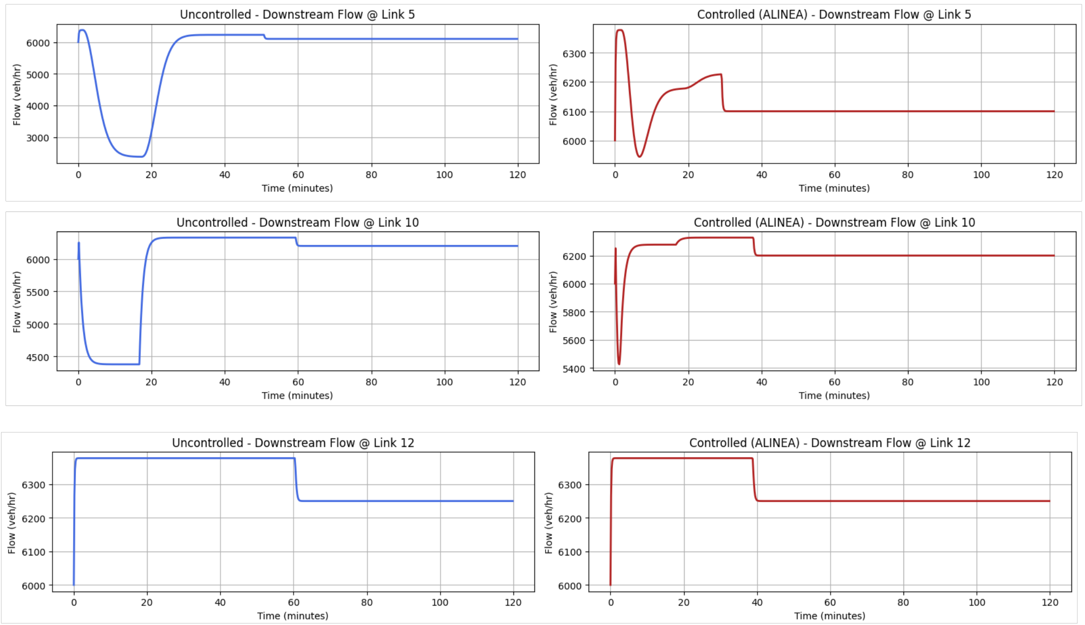

Figure 3: Downstream Flow along Links 5, 10, and 12 for the Standard Traffic Pattern.

2.1.2 Overall Average Density Across All Links

The uncontrolled network experienced widespread, prolonged high average densities. ALINEA significantly lowered and stabilized this average, demonstrating successful system-wide congestion management.

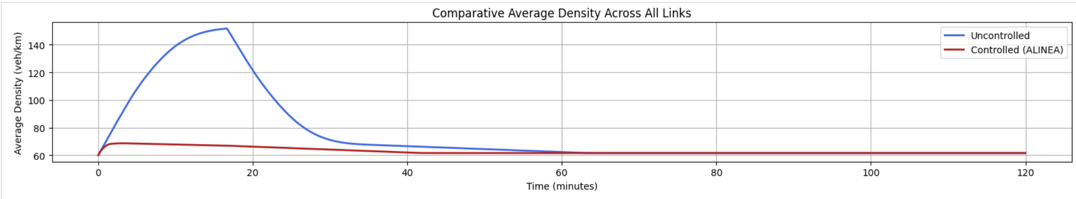

Figure 4: Comparative Density for the Standard Traffic Pattern.

2.1.3 Density Heatmaps

Uncontrolled heatmaps vividly showed congestion forming and propagating backward, persisting for a considerable duration. ALINEA's heatmaps displayed a largely uniform, low-density profile, confirming effective congestion prevention throughout the network.

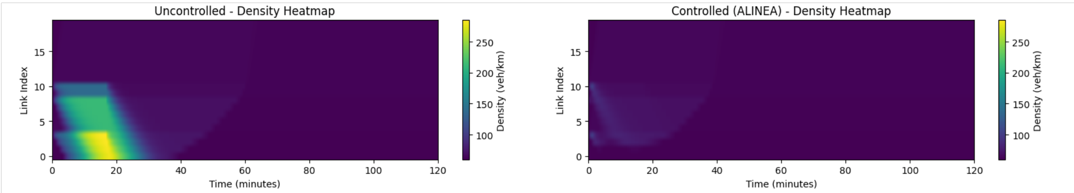

Figure 5: Comparative Heatmaps for the Standard Traffic Pattern.

2.1.4 Summary for Standard Traffic Pattern:

For this typical demand pattern, ALINEA proved remarkably effective. It successfully prevented severe congestion, maintained higher throughput, and facilitated quicker recovery, significantly improving overall traffic conditions and system efficiency.

2.2 Persistent High Demand

This scenario represents a more challenging situation with consistently high traffic demand throughout the simulation, crucial for understanding the controller's sustained performance under prolonged stress.

2.2.1 Analysis of Persistent High Demand Results

- **Ramp Traffic Flow (Links 4, 9, 11):** Uncontrolled ramp flow directly matched the continuously high demand. Under ALINEA, ramp flows were aggressively restricted, often driven down to the minimum metering rate (100 veh/hr), clearly prioritizing mainline protection.

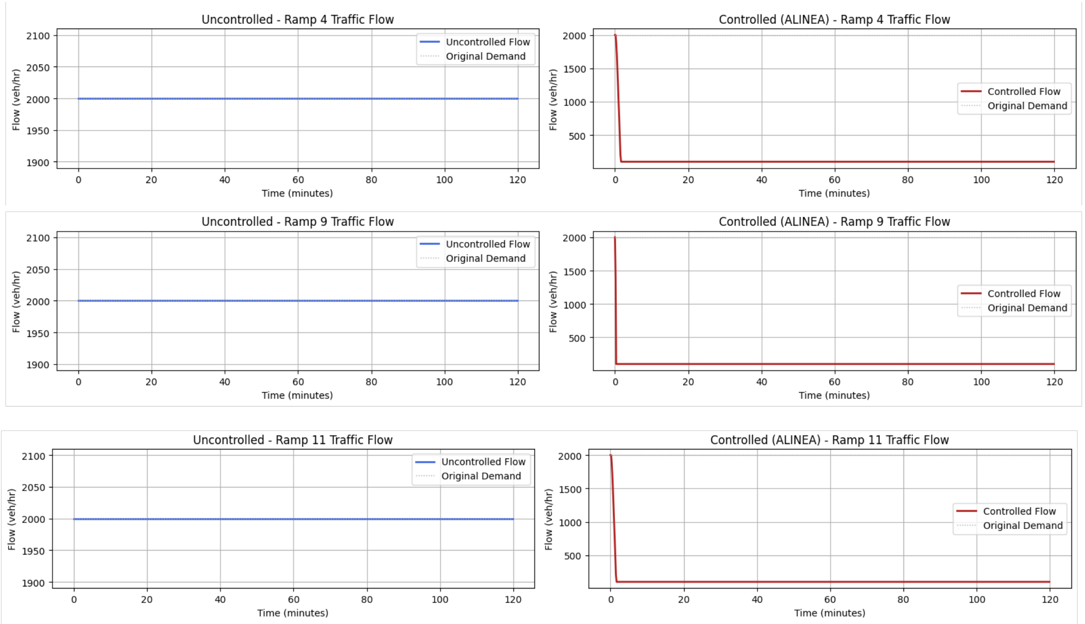

Figure 6: Ramp traffic flow along Links 4, 9, and 11 for the Persistent High Demand scenario.

- **Downstream Density (Links 5, 10, 12):** Uncontrolled densities rapidly peaked and remained at maximum capacity (300 veh/km), signifying immediate and severe, sustained mainline congestion. Conversely, ALINEA successfully kept downstream densities near the target (60 veh/km), preventing prolonged gridlock.

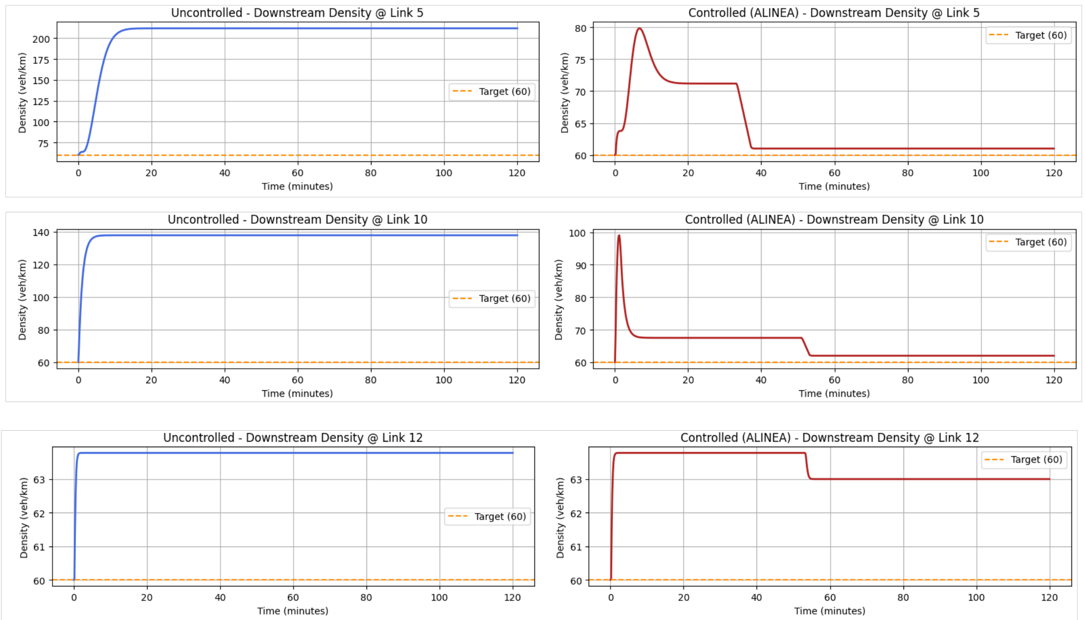

Figure 7: Downstream Density along Links 5, 10, and 12 for the Persistent High Demand scenario.

- **Downstream Flow (Links 5, 10, 12):** The uncontrolled downstream flow severely dropped due to mainline congestion, indicating highly inefficient operation. ALINEA maintained significantly higher and more consistent mainline throughput by effectively controlling density and preventing capacity drops.

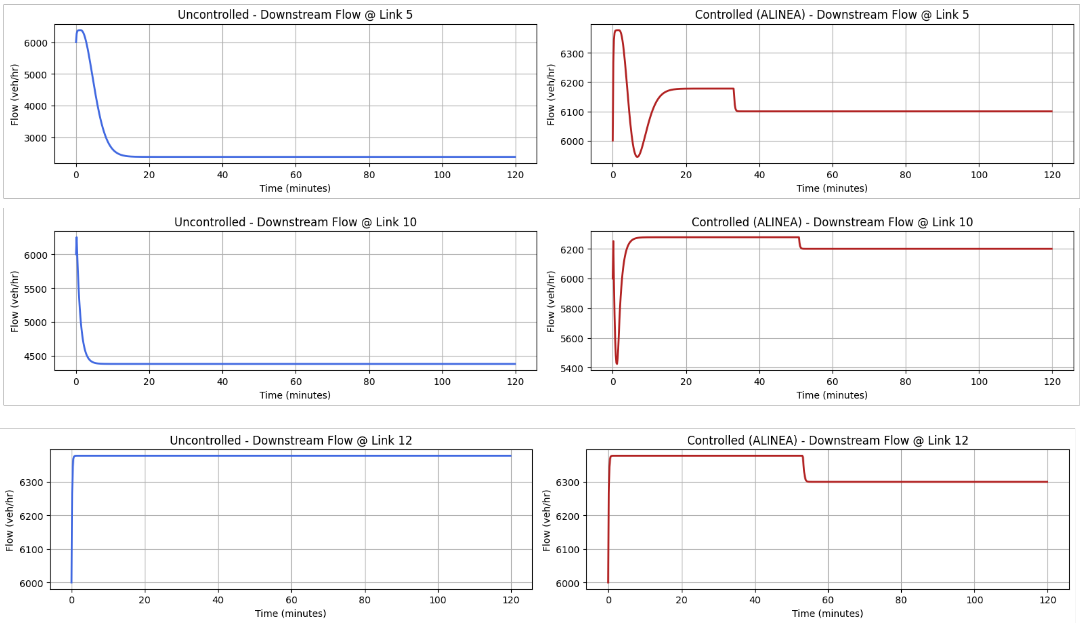

Figure 8: Downstream Flow along Links 5, 10, and 12 for the Persistent High Demand scenario.

2.2.2 Overall Average Density Across All Links

The uncontrolled system endured system-wide, sustained high average densities, signifying a persistent traffic jam. ALINEA drastically reduced and stabilized this average, demonstrating effective network-wide congestion management even under continuous stress.

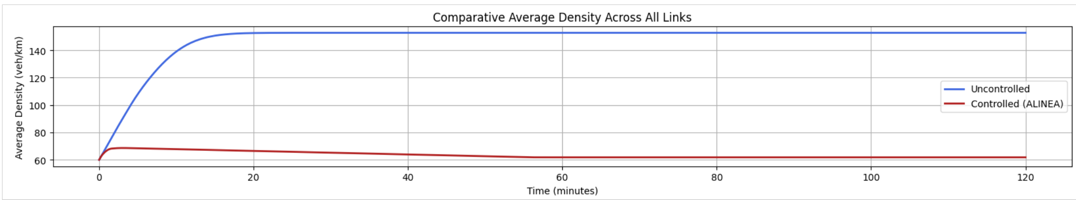

Figure 9: Comparative Density for the Persistent High Demand scenario.

2.2.3 Density Heatmaps

Uncontrolled heatmaps showed a pervasive region of extremely high density covering almost the entire network. In stark contrast, ALINEA's heatmaps revealed a mostly uniform, low-density state, confirming successful congestion prevention under continuous high demand.

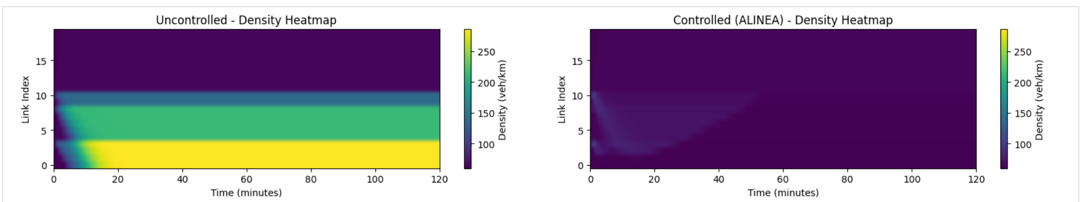

Figure 10: Comparative Heatmaps for the Persistent High Demand scenario.

2.2.4 Summary for Persistent High Demand:

This demanding scenario highlighted ALINEA's strength in protecting the mainline and maximizing its throughput. However, this came at the cost of aggressive ramp metering, which implicitly leads to significant delays and queues on the on-ramps.

2.3 Fluctuating Demand

This scenario introduces an oscillatory demand pattern, testing the controller's dynamic responsiveness and adaptability to continuously changing traffic conditions.

2.3.1 Analysis of Fluctuating Demand Results

- **Ramp Traffic Flow (Links 4, 9, 11):** Uncontrolled ramp flow perfectly tracked the fluctuating demand. ALINEA demonstrated aggressive metering during demand peaks to prevent congestion.

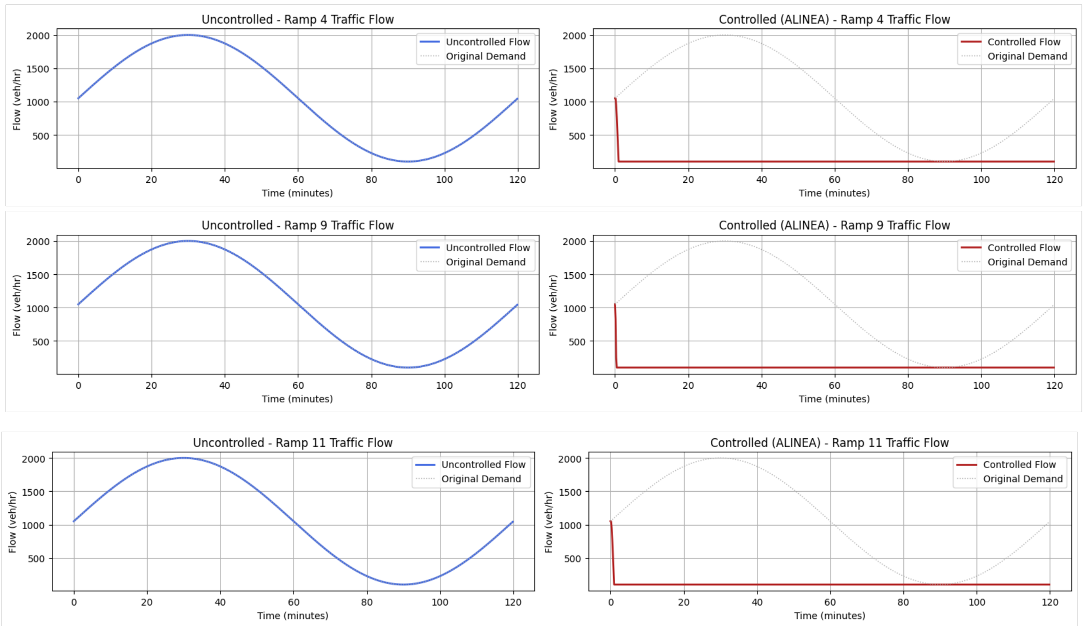

Figure 11: Ramp traffic flow along Links 4, 9, and 11 for the Fluctuating Demand scenario.

- **Downstream Density (Links 5, 10, 12):** Uncontrolled downstream densities exhibited oscillatory peaks indicative of congestion, which recovered slowly. ALINEA adaptively maintained densities close to the target (60 veh/km), effectively preventing severe congestion spikes throughout the fluctuations.

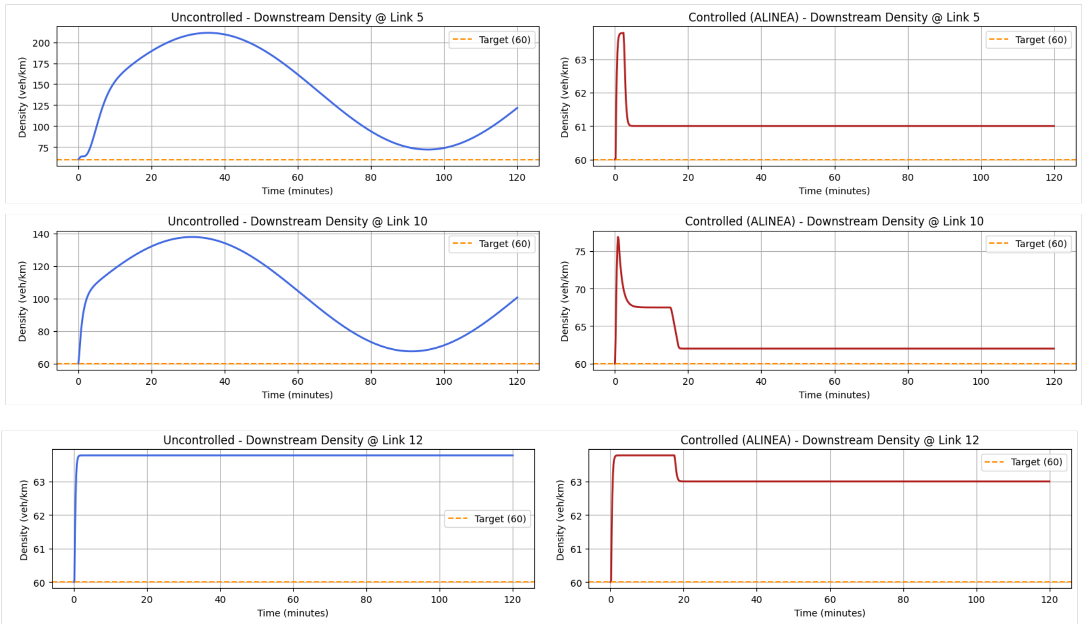

Figure 12: Downstream Density along Links 5, 10, and 12 for the Fluctuating Demand scenario.

- **Downstream Flow (Links 5, 10, 12):** Uncontrolled flow experienced capacity drops during congestion peaks. ALINEA, by mitigating density build-up, consistently ensured higher and more stable mainline flow, optimizing throughput even with varying demand.

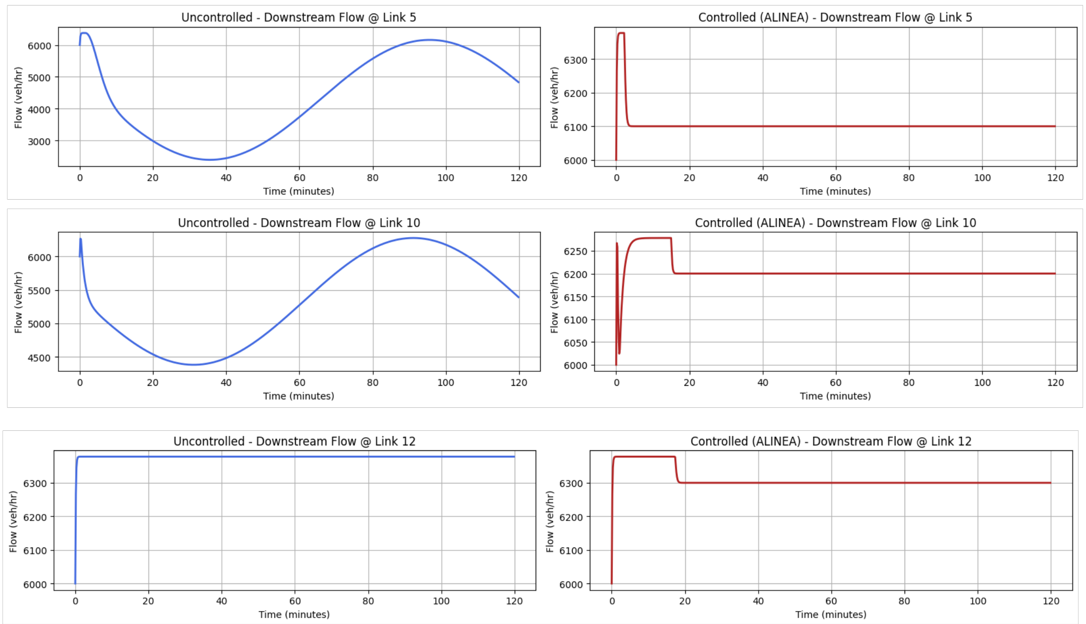

Figure 13: Downstream Flow along Links 5, 10, and 12 for the Fluctuating Demand scenario.

2.3.2 Overall Average Density Across All Links

The uncontrolled average density fluctuated with high peaks, reflecting cyclical congestion. ALINEA maintained a stable, significantly lower average density near the target, showcasing robust network efficiency under dynamic conditions.

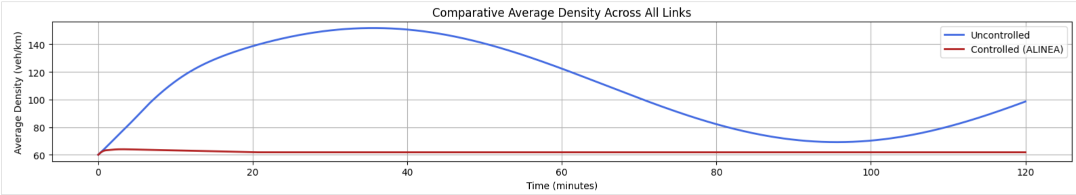

Figure 14: Comparative Density for the Fluctuating Demand scenario.

2.3.3 Density Heatmaps

Uncontrolled heatmaps clearly showed cyclical congestion forming and propagating. In stark contrast, ALINEA's heatmaps consistently displayed a low-density profile, confirming effective dynamic congestion prevention across the network.

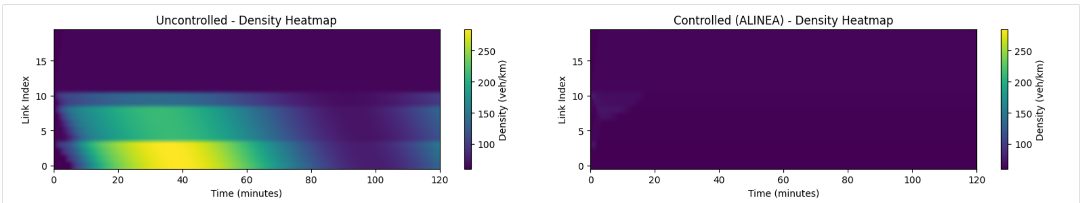

Figure 15: Comparative Heatmaps for the Fluctuating Demand scenario.

2.3.4 Summary for Fluctuating Demand:

This scenario strongly underscored ALINEA's adaptability and robustness. The controller successfully managed mainline density and maintained high throughput by dynamically adjusting to oscillating demand patterns, proving well-suited for real-world conditions.

3 Overall Conclusion

Across all simulated scenarios, the ALINEA-like controller consistently demonstrated superior performance in managing mainline traffic flow compared to the uncontrolled system. Its primary strength lies in effectively preventing severe mainline congestion and maintaining higher throughput by regulating ramp entries, even under challenging and dynamic demand patterns. Critically, while ALINEA successfully shifts congestion from the mainline, this often comes at the cost of aggressive metering, potentially leading to increased queue lengths and delays on the on-ramps. Nevertheless, for applications prioritizing mainline efficiency and reliability, ALINEA proves to be a robust and adaptable solution.