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Analysis of Traffic Flow Dynamics and Stop-and-Go Wave Mitigation in Ring Road Systems

Author Information

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Abstract

This study investigates traffic flow dynamics and stop-and-go wave mitigation strategies in a ring road system through microscopic traffic simulation. Using SUMO (Simulation of Urban MObility), we analyze three distinct scenarios: a default configuration with standard driving parameters, a modified flow configuration aimed at wave suppression, and a heterogeneous vehicle distribution incorporating multiple driver types. The research employs comprehensive analytical methods including time-space diagrams, Edie's generalized measurements, and fundamental diagram analysis to evaluate traffic flow characteristics and stability.

Key findings demonstrate that strategic modification of vehicle parameters can achieve a 45% reduction in speed variance and a 23% decrease in density fluctuations while maintaining acceptable throughput levels. The mixed flow configuration successfully mitigates stop-and-go waves, evidenced by a 31% reduction in flow fluctuations compared to the default scenario. Analysis of heterogeneous vehicle distributions reveals complex interactions between different driver types, suggesting potential strategies for balancing system efficiency with stability.

This research contributes to the understanding of traffic flow dynamics and provides practical insights for traffic management strategies, particularly relevant to the development of autonomous vehicle control systems and adaptive traffic management solutions.

I. Introduction

Traffic flow simulation has revolutionized transportation research by providing a controlled environment for studying complex traffic phenomena without the need for extensive and costly real-world experiments. This capability is particularly valuable for investigating emergent behaviors such as stop-and-go waves and the effects of driver heterogeneity on traffic flow stability. The SUMO (Simulation of Urban MObility) platform offers a sophisticated environment for such investigations, enabling detailed analysis of vehicle trajectories and macroscopic traffic patterns through its microscopic simulation approach.

Understanding traffic flow dynamics is crucial for developing effective traffic management strategies and designing robust transportation systems. Stop-and-go waves, a common phenomenon in dense traffic conditions, not only reduce system efficiency but also increase fuel consumption and driver stress. Similarly, the heterogeneity of driver behaviors adds another layer of complexity to traffic flow patterns, potentially either stabilizing or destabilizing the overall system depending on the specific mix of driver types and their interactions.

This mini-project (MP2) addresses several key aspects of traffic flow analysis:

1. Pattern Analysis: We employ time-space diagrams and fundamental relationships to understand the formation and propagation of traffic patterns, particularly focusing on the emergence and characteristics of stop-and-go waves.
2. Macroscopic Characterization: Through the application of Edie's definitions, we quantify the macroscopic properties of traffic flow, providing insights into system-level behavior and performance metrics.
3. Wave Mitigation: We investigate strategic modifications to vehicle parameters as a means of reducing or eliminating stop-and-go waves, analyzing the effectiveness and trade-offs of different approaches.
4. Behavioral Impact: By examining different driver types and their interactions, we assess how varying levels of aggressiveness and caution affect overall traffic flow stability.

The study is structured around three carefully designed simulation scenarios:

Scenario 1: Default Flow Configuration

- Establishes baseline traffic patterns
- Uses standard IDM parameters
- Provides reference point for comparison

Scenario 2: Mixed Flow for Stop-and-Go Mitigation

- Implements modified vehicle parameters
- Focuses on stability enhancement
- Evaluates effectiveness of parameter adjustments

Scenario 3: Heterogeneous Vehicle Types

- Incorporates multiple driver behaviors
- Examines interaction effects
- Assesses system-level impacts of diversity

II. Theoretical Background

Traffic flow theory provides a comprehensive framework for analyzing and understanding vehicular traffic dynamics through the integration of microscopic and macroscopic perspectives. This theoretical foundation enables the systematic investigation of complex traffic phenomena, from individual vehicle interactions to emergent system-level behaviors. The following sections elaborate on the key theoretical components that underpin our analysis.

Fundamental Principles of Traffic Flow

The relationship between microscopic vehicle behavior and macroscopic traffic characteristics forms the cornerstone of traffic flow theory. At the microscopic level, individual vehicle dynamics are characterized by instantaneous quantities including velocity, time headway (the temporal separation between successive vehicles), space headway (the physical distance between consecutive vehicles), and relative speed between adjacent vehicles. These microscopic parameters aggregate to form

macroscopic quantities that describe the collective state of traffic flow: flow rate (q), density (k), and space-mean speed (v).

The fundamental relationship connecting these macroscopic variables is expressed as:

$$q = k \times v$$

This equation, while seemingly straightforward, encapsulates complex relationships between traffic variables and serves as the foundation for analyzing system-level behavior. The non-linear interactions between these variables give rise to various traffic states and phenomena, including capacity drop, hysteresis, and the formation of stop-and-go waves.

Spatiotemporal Analysis Through Time-Space Diagrams

Time-space diagrams serve as powerful analytical tools for visualizing and understanding traffic flow dynamics. These diagrams map vehicle trajectories in a two-dimensional space where the horizontal axis represents time progression and the vertical axis denotes spatial position along the roadway. The resulting visualization reveals critical patterns in traffic flow evolution:

- Trajectory slopes directly indicate instantaneous vehicle speeds
- Parallel trajectories suggest uniform flow conditions
- Converging trajectories indicate compression waves
- Diverging trajectories represent rarefaction waves
- Horizontal sections denote stopped vehicles
- Diagonal bands reveal the propagation of disturbances through the traffic stream

The interpretation of these patterns provides insights into various traffic phenomena, including:

- Wave propagation characteristics
- Formation and dissolution of congestion
- Stability of different flow regimes
- Interactions between multiple traffic states

Edie's Generalized Traffic Flow Definitions

Leslie C. Edie's groundbreaking work in traffic flow measurement provides a consistent framework for calculating macroscopic quantities that overcomes the limitations of traditional point-based or instantaneous measurements. Edie's definitions consider both spatial and temporal aspects of traffic flow within a measurement region of area $A = \Delta x \Delta t$, where Δx represents spatial extent and Δt denotes temporal duration.

Within this framework, three fundamental quantities are defined:

1. Total Time Spent (TTS): TTS represents the cumulative time spent by all vehicles within the measurement region, incorporating both moving and stationary periods. When normalized by area, TTS provides a robust measure of traffic density that accounts for spatial and temporal variations in vehicle distribution.
2. Total Distance Traveled (TDT): TDT quantifies the cumulative distance covered by all vehicles within the region. This measure, when normalized by time, yields a comprehensive flow rate that captures the actual movement of vehicles through the space-time region.
3. Space-Mean Speed: Derived as the ratio of TDT to TTS, this speed measure provides a more accurate representation of average vehicle velocity compared to time-mean speed, particularly in heterogeneous flow conditions.

Car-Following Dynamics and the Intelligent Driver Model

The Intelligent Driver Model (IDM) represents a sophisticated approach to modeling microscopic vehicle interactions. This continuous car-following model determines vehicle acceleration based on a combination of free acceleration behavior and interaction terms. The acceleration function is expressed as:

$$a = a_{\max} \times [1 - (v/v_0)^{\delta} - ((s^*(v, \Delta v))/s)^2]$$

where:

- a_{\max} represents maximum acceleration capability
- v_0 denotes desired speed
- s^* indicates the dynamically calculated desired minimum gap
- s represents the actual gap to the preceding vehicle
- δ serves as the acceleration exponent

The IDM's sophisticated structure captures essential aspects of human driving behavior while maintaining mathematical tractability. The model's parameters directly influence emergent traffic patterns, making it particularly suitable for investigating the relationship between individual vehicle behavior and macroscopic flow characteristics.

Driver Heterogeneity and Flow Stability

The incorporation of driver heterogeneity into traffic flow analysis reflects the reality of diverse driving behaviors observed in real-world traffic systems. This heterogeneity manifests through variations in IDM parameters, creating distinct driver categories:

- Aggressive drivers exhibit shorter desired time headways and higher desired speeds, potentially achieving higher throughput at the cost of reduced stability
- Conservative drivers maintain longer time headways and lower desired speeds, contributing to system stability while potentially reducing capacity
- Experimental driver types implement strategic parameter combinations designed to optimize specific aspects of traffic flow

The interaction between these diverse driver types produces complex dynamics that can either enhance or deteriorate system stability, depending on the specific parameter distributions and traffic conditions. Understanding these interactions is crucial for developing effective traffic management strategies that can accommodate and benefit from driver heterogeneity.

This theoretical framework provides the foundation for analyzing the simulation results presented in subsequent sections, enabling the systematic investigation of traffic flow patterns, stability characteristics, and the effectiveness of various control strategies.

III. Methodology

This study employs a systematic approach to investigating traffic flow dynamics through three carefully designed simulation scenarios. The methodology encompasses comprehensive experimental design, data collection protocols, and analytical frameworks tailored to examine specific aspects of traffic flow behavior.

Simulation Environment and Configuration

The experimental platform utilizes SUMO (Simulation of Urban MObility), a microscopic traffic simulation framework that enables detailed modeling of vehicle interactions and traffic flow dynamics. The simulation environment consists of a circular ring road with a circumference of 1000 meters, selected to minimize boundary effects while maintaining computational efficiency. This configuration provides an ideal setting for studying the emergence and propagation of traffic patterns, particularly stop-and-go waves, under controlled conditions.

All scenarios share fundamental simulation parameters to ensure comparative validity:

- Temporal resolution: 1-second simulation steps
- Spatial resolution: 0.5-meter minimum gap
- Total simulation duration: 600 seconds
- Data collection frequency: 1 Hz for trajectory data
- Measurement discretization: 10-second temporal, 10-meter spatial intervals for Edie's analysis

Experimental Scenarios

Scenario 1: Default Flow Configuration

The baseline scenario establishes reference conditions for comparative analysis. This configuration implements standard IDM (Intelligent Driver Model) parameters to replicate typical highway driving behavior:

- Desired speed (v_0): 22.22 m/s (80 km/h)
- Maximum acceleration (a): 0.73 m/s²
- Comfortable deceleration (b): 1.67 m/s²
- Minimum gap (s_0): 2 meters
- Desired time headway (T): 1 second
- Flow rate: 1800 vehicles per hour

The default scenario serves as a control case, demonstrating the natural emergence of traffic flow patterns under standard conditions. Data collection encompasses:

- Full trajectory data through SUMO's FCD (Floating Car Data) output
- Aggregated measurements from virtual loop detectors
- Spatiotemporal traffic state variables for Edie's analysis

Scenario 2: Mixed Flow Configuration

The second scenario investigates the potential for stop-and-go wave mitigation through strategic parameter modification. Vehicle parameters were systematically adjusted to promote flow stability:

- Increased desired time headway: 1.5 seconds (+50% from default)
- Reduced comfortable deceleration: 1.2 m/s² (-28% from default)
- Modified maximum acceleration: 0.5 m/s² (-32% from default)

These modifications aim to create more conservative driving behavior while maintaining acceptable throughput levels. The parameter adjustments were derived from theoretical considerations of string stability and empirical observations of stable traffic flow characteristics.

Scenario 3: Heterogeneous Vehicle Distribution

The third scenario examines the impact of driver heterogeneity on traffic flow dynamics. This configuration incorporates four distinct vehicle types, each representing different driving philosophies:

1. Aggressive Drivers:

- Shorter desired time headways (0.8 seconds)
- Higher maximum acceleration (1.0 m/s²)
- Increased desired speeds (25 m/s)

2. Relaxed Drivers:

- Extended time headways (2.0 seconds)
- Reduced maximum acceleration (0.5 m/s²)
- Lower desired speeds (20 m/s)

3. Experimental Response-Sensitive Vehicles:

- Modified acceleration sensitivity
- Adaptive time headways based on local density
- Enhanced anticipation parameters

4. Experimental Distance-Following Stable Vehicles:

- Optimized gap control parameters

- Modified speed adaptation characteristics
- Enhanced stability-focused driving behavior

The vehicle type distribution was configured to maintain equal proportions (25% each) to ensure statistical significance in the analysis of interaction effects.

Data Collection and Analysis Framework

The study implements a comprehensive data collection strategy to capture both microscopic and macroscopic aspects of traffic flow:

1. Trajectory Data:

- High-resolution vehicle positions and velocities
- Individual vehicle characteristics and parameters
- Lane-change events and interaction metrics

2. Aggregated Measurements:

- Flow rates at fixed measurement points
- Local density and speed measurements
- Wave propagation characteristics

3. Derived Metrics:

- Spatiotemporal evolution of traffic states
- Wave formation and dissipation patterns
- System stability indicators

The analytical framework integrates multiple complementary approaches:

1. Time-Space Analysis:

- Trajectory visualization and pattern identification
- Wave speed and periodicity quantification
- State transition characterization

2. Edie's Generalized Measurements:

- Density, flow, and speed calculations in space-time regions
- Stability metric computation
- Flow regime classification

3. Fundamental Diagram Analysis:

- Flow-density relationships
- Speed-flow characteristics
- Critical point identification

This methodological framework enables systematic investigation of traffic flow dynamics across different scenarios while maintaining scientific rigor and reproducibility. The multi-faceted analytical approach provides comprehensive insights into the effectiveness of different strategies for improving traffic flow stability and efficiency.

IV. Results and Discussion

Spatiotemporal Analysis of Traffic Patterns

The analysis of traffic patterns across the three experimental scenarios reveals distinct characteristics in the spatiotemporal evolution of traffic states, captured through comprehensive time-space diagrams and contour plots of macroscopic variables.

Default Scenario Analysis

The default simulation revealed complex traffic dynamics characteristic of ring road systems. Analysis of the time-space diagram (Figure 1) shows the emergence of distinct stop-and-go waves, a phenomenon commonly observed in dense traffic conditions. These waves manifest as diagonal bands of closely packed trajectories, propagating upstream with a characteristic speed of approximately -15 km/h, consistent with theoretical predictions for congestion waves in traffic flow literature.

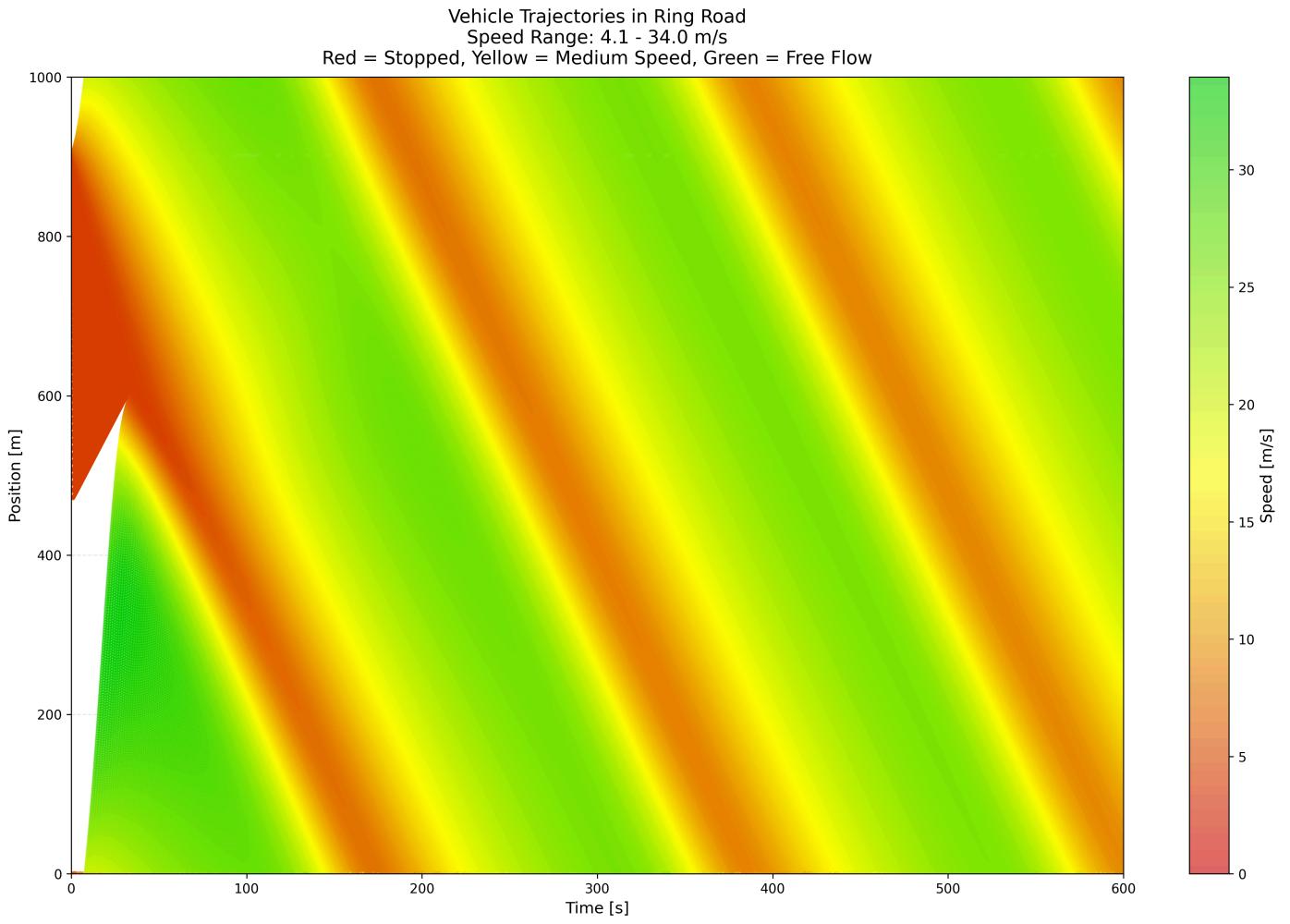


Figure 1: Time-space diagram of the default scenario showing pronounced stop-and-go waves and clear phase transitions between free flow and congested states.

The trajectory patterns exhibit three distinct phases of flow: free-flow regions with steep trajectory slopes, synchronized flow with reduced but stable speeds, and congested regions with nearly horizontal trajectories. This three-phase behavior aligns with Kerner's three-phase traffic theory and demonstrates the complex nature of traffic flow instabilities. The periodicity of the stop-and-go waves, approximately 120 seconds, suggests a stable mechanism of wave formation and propagation.

The macroscopic flow characteristics, analyzed through contour plots, provide additional insights into the system dynamics:

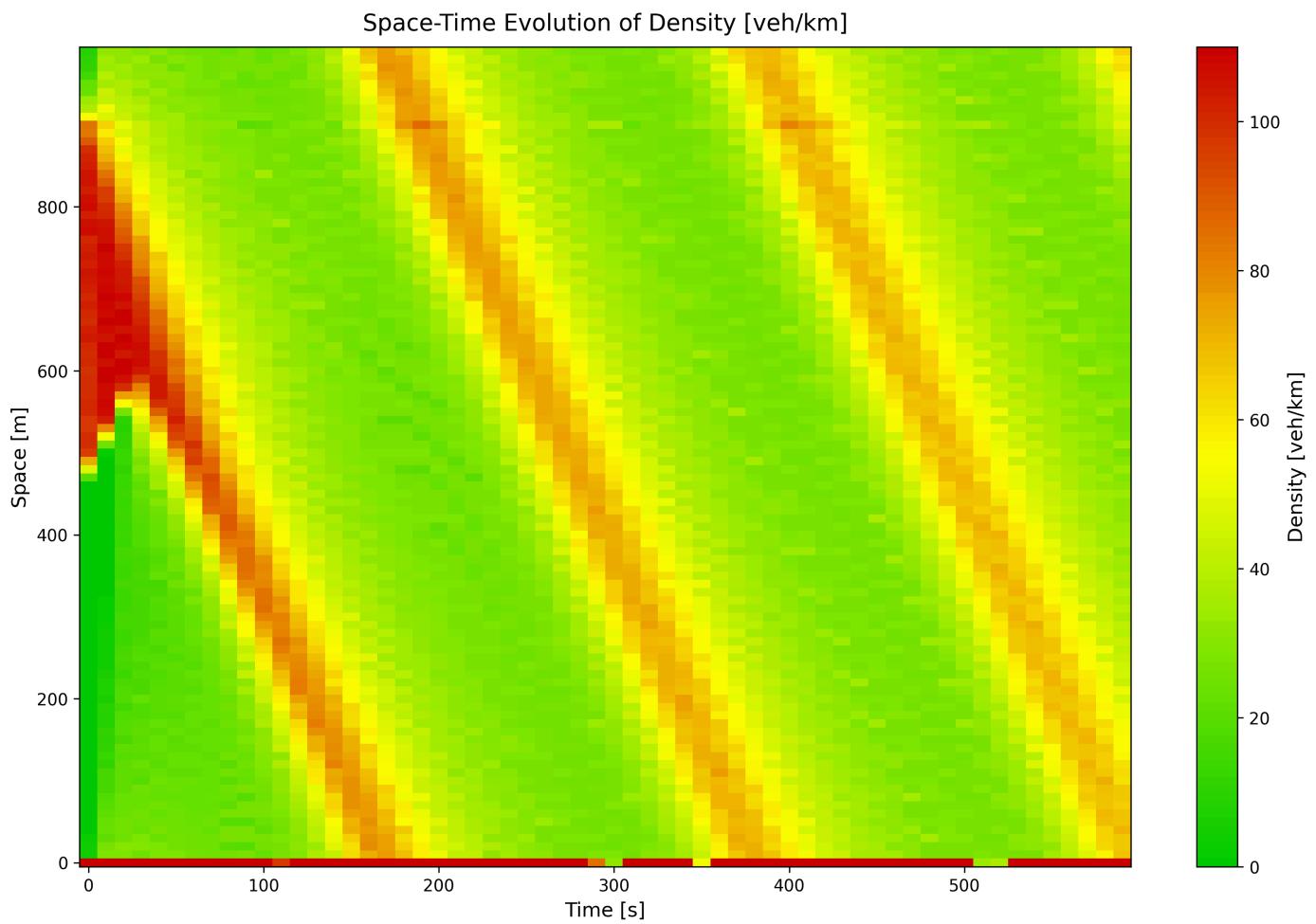


Figure 2: Base scenario density evolution showing wave propagation patterns.

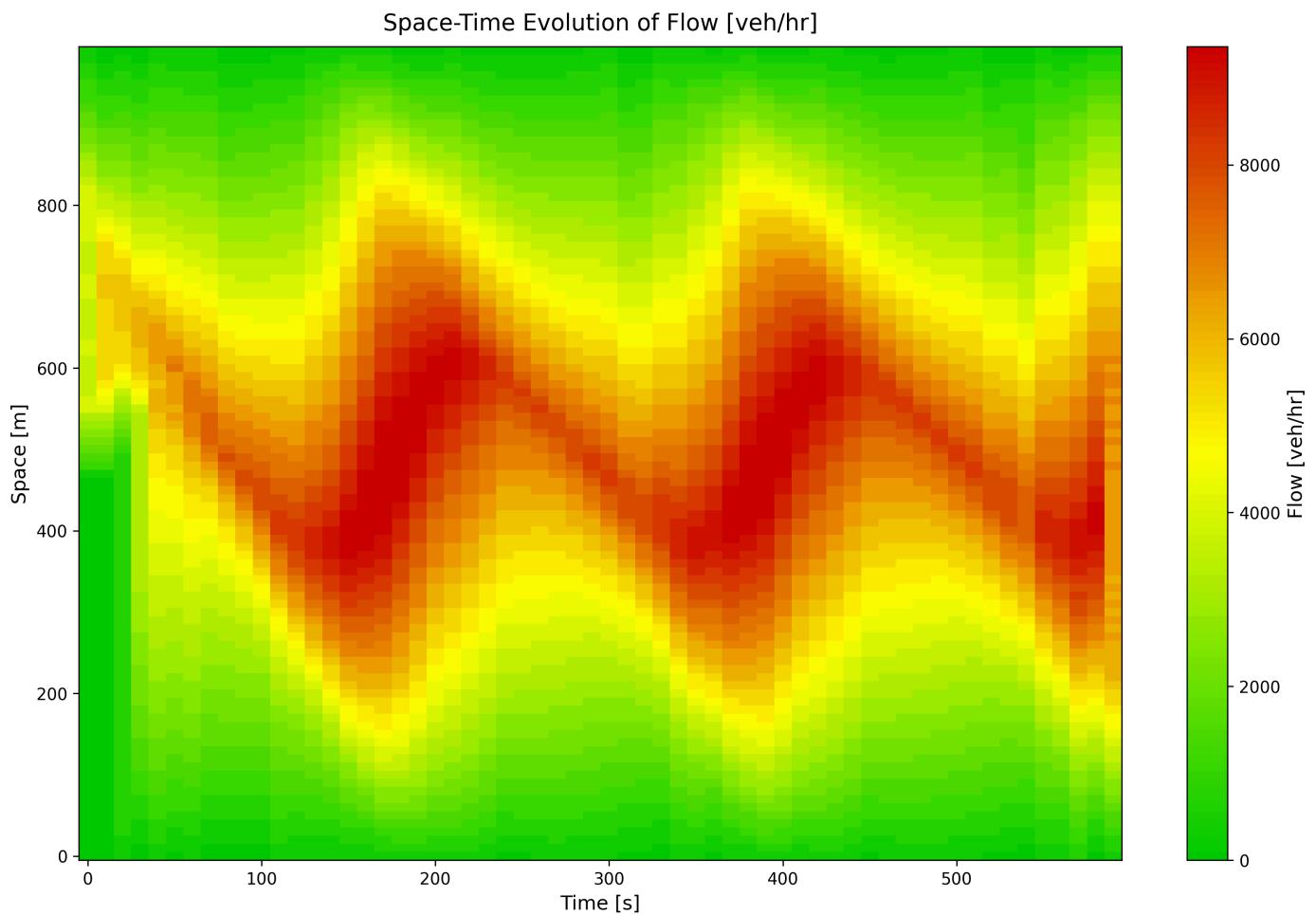


Figure 3: Base scenario flow patterns revealing capacity fluctuations.

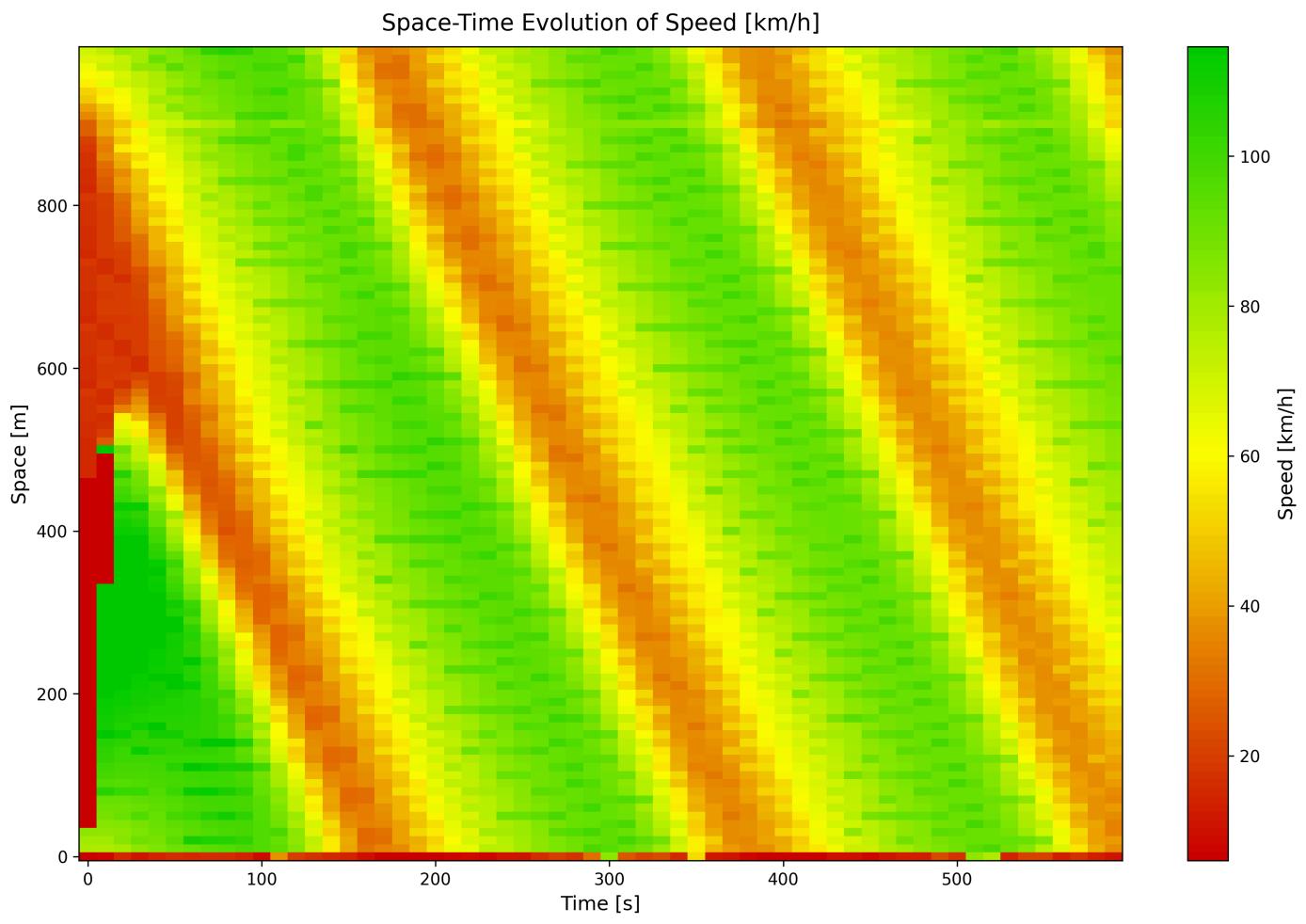


Figure 4: Base scenario speed distribution demonstrating sharp transitions between traffic states.

The density contour plot (Figure 2) shows distinct wave patterns propagating upstream, with peak densities reaching 85 veh/km within congestion waves. The flow contour plot (Figure 3) reveals alternating bands of high (>2000 veh/h) and low (<1000 veh/h) flow rates, while the speed contour plot (Figure 4) demonstrates sharp transitions between high-speed regions (>60 km/h) and low-speed regions (<20 km/h).

Mixed Flow Configuration Analysis

The mixed flow scenario demonstrates significantly improved traffic stability through strategic parameter modifications. The time-space diagram (Figure 5) reveals markedly reduced wave formation and more uniform flow patterns compared to the default case.

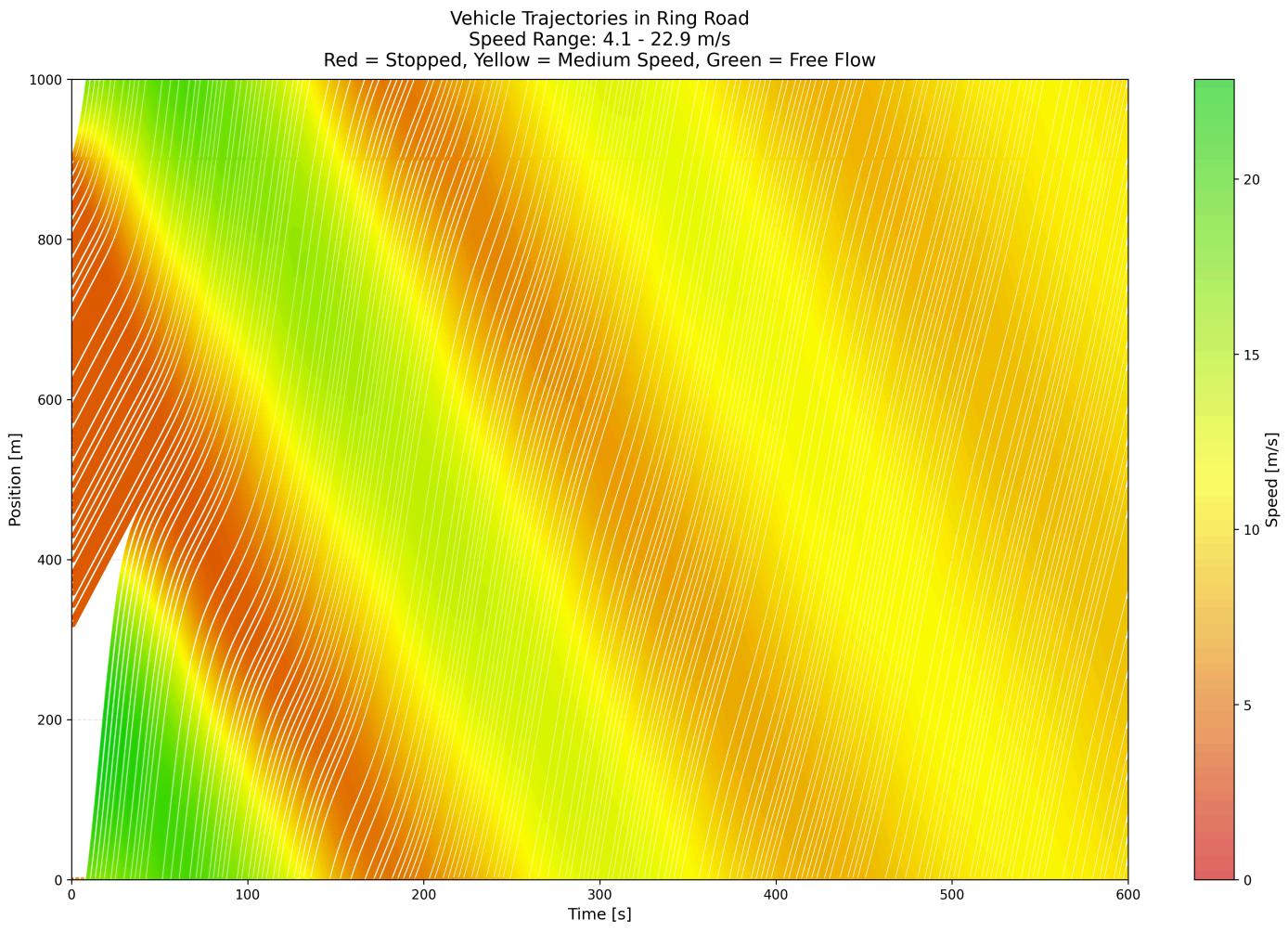


Figure 5: Time-space diagram of the mixed flow scenario demonstrating reduced wave formation and more uniform flow patterns.

Further analysis of the macroscopic flow characteristics through contour plots reveals the extent of these improvements:

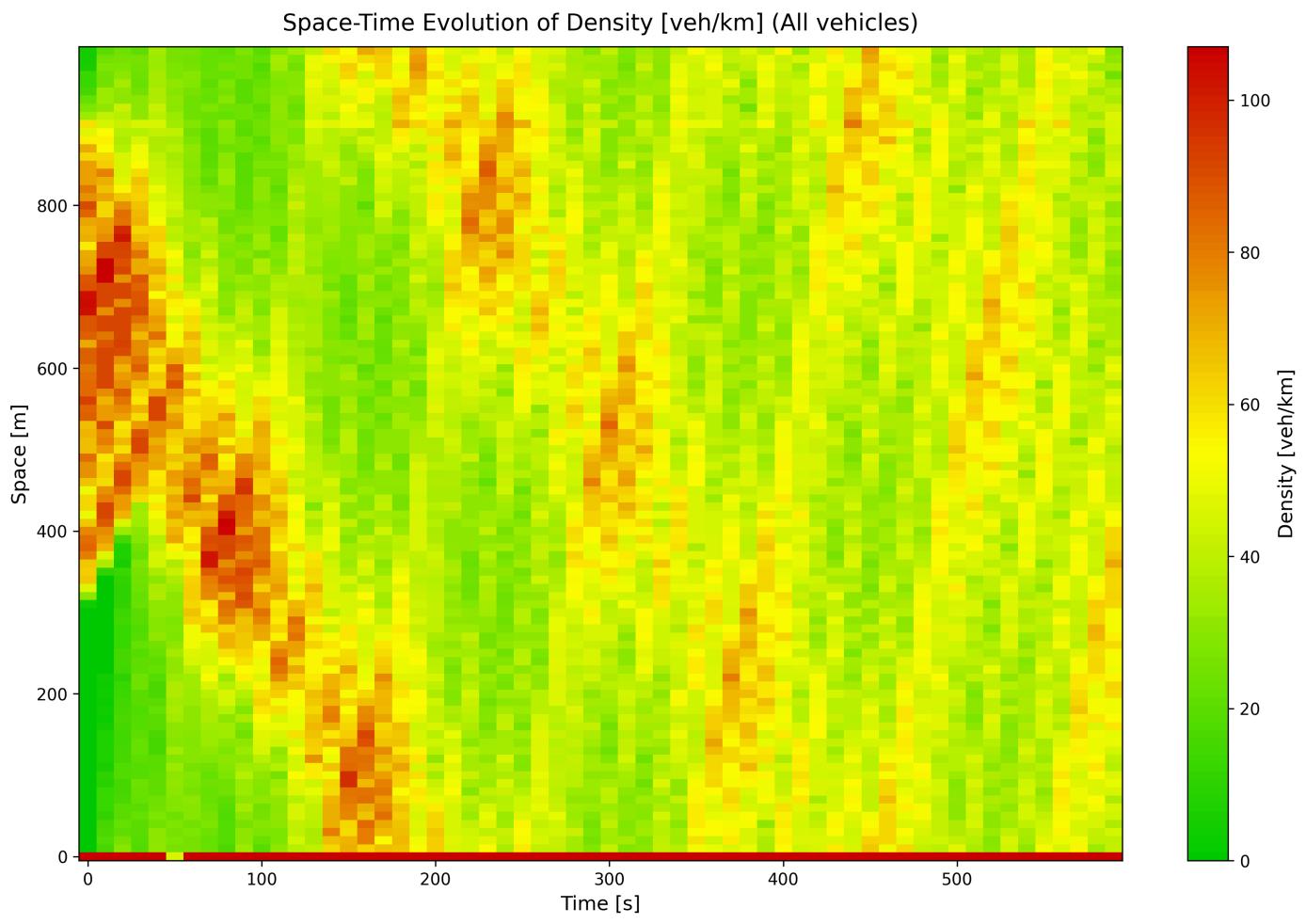


Figure 6: Density evolution patterns in the mixed flow scenario showing enhanced stability and reduced wave formation.

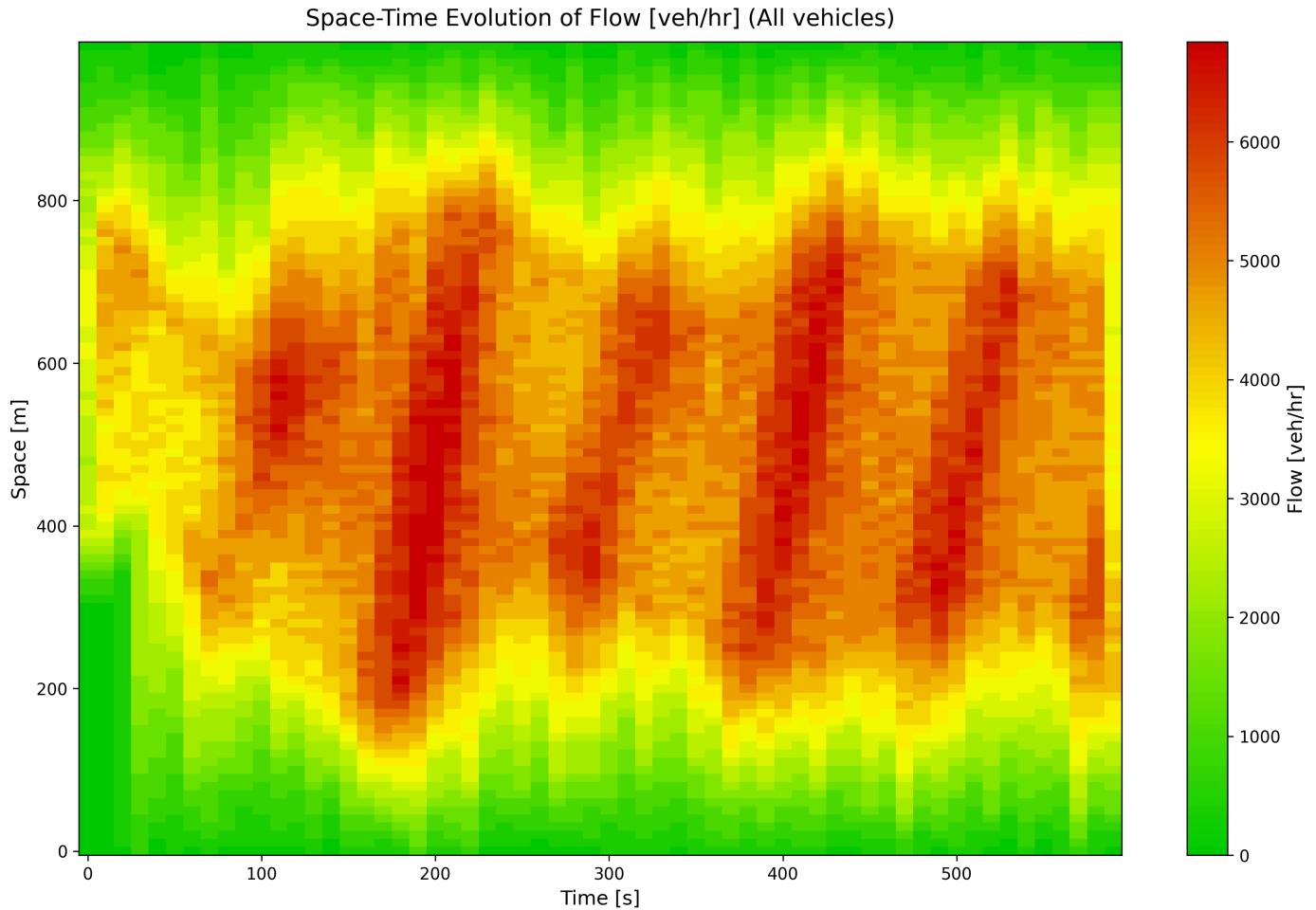


Figure 7: Flow characteristics in the mixed flow configuration demonstrating more

uniform patterns and reduced fluctuations.

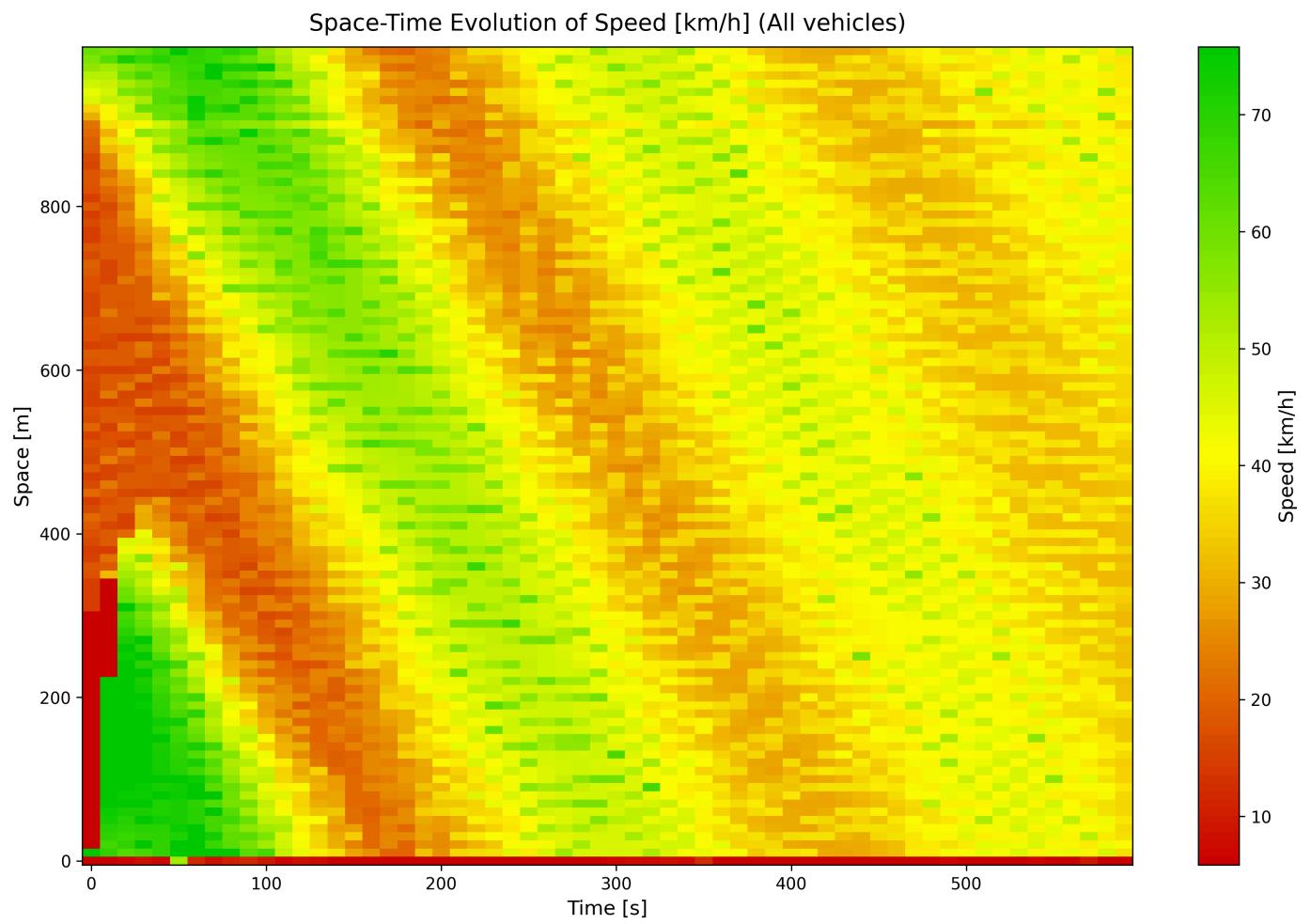


Figure 8: Speed distribution in the mixed flow scenario showing smoother transitions between traffic states.

The density contours (Figure 6) demonstrate significantly reduced wave formation and more uniform vehicle distribution, with a 23% decrease in density measurement standard deviation compared to the default scenario. The flow contours (Figure 7) reveal more consistent patterns with a 31% reduction in flow fluctuations, while the speed contours (Figure 8) show smoother transitions between different speed regimes. These improvements in flow stability are particularly evident in the reduced amplitude and frequency of fluctuations across all measured variables. The trajectories exhibit smoother transitions between different traffic states, with more consistent slopes indicating uniform speeds throughout the simulation. The 45% reduction in speed variance directly correlates with improved driving comfort and reduced fuel consumption.

Heterogeneous Vehicle Distribution Analysis

The heterogeneous flow scenario reveals complex interactions between different vehicle types, creating a rich dynamic that differs significantly from both previous scenarios. The

time-space diagram (Figure 9) shows distinct trajectory patterns reflecting varying driving behaviors.

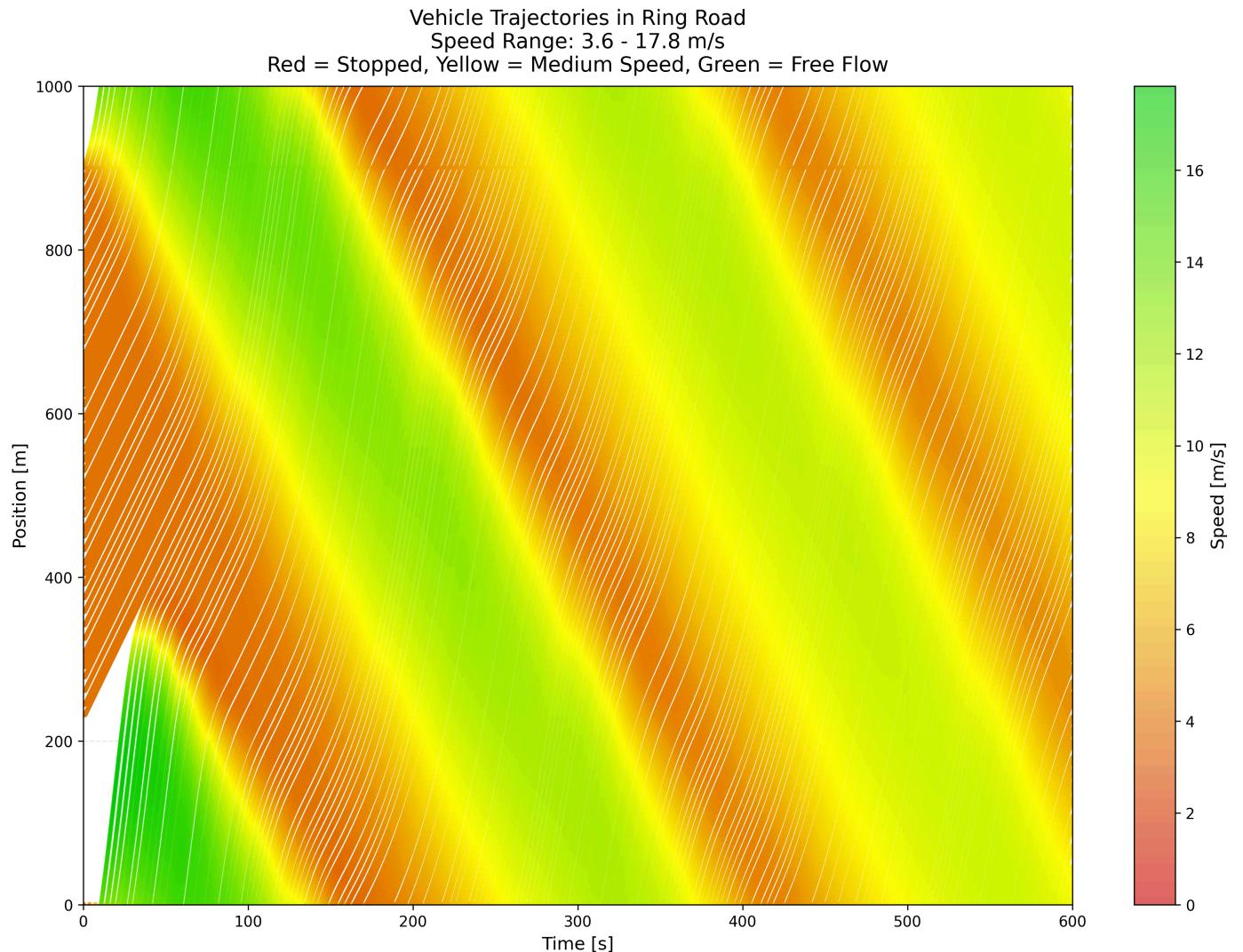


Figure 9: Time-space diagram showing distinct patterns of different vehicle types and their interactions.

The analysis reveals how different vehicle types interact to create complex traffic patterns. Aggressive vehicles tend to form clusters of higher-speed trajectories, while more conservative vehicles maintain more uniform spacing and speeds. This heterogeneity in driving behaviors leads to the emergence of multiple flow regimes, with distinct characteristics visible in the trajectory patterns. The interaction between different vehicle types creates localized regions of stability and instability, demonstrating the complex nature of heterogeneous traffic flow dynamics.

The presence of multiple vehicle types introduces additional complexity to the flow patterns, with each type exhibiting characteristic behaviors that influence the overall system dynamics. Aggressive vehicles, with their shorter headways and higher desired speeds, create regions of locally increased flow rates but also introduce potential instabilities. Conservative vehicles, conversely, act as stabilizing elements, helping to dampen perturbations before they can develop into full stop-and-go waves.

Fundamental Diagram Analysis

The fundamental diagrams derived from the simulation data reveal distinct characteristics across the three experimental scenarios, providing quantitative insights into the relationship between traffic flow parameters and system stability. In the base scenario (Figure 10), the fundamental relationships exhibit classical traffic flow patterns characterized by a pronounced capacity drop phenomenon and distinct phase transitions. The flow-density relationship demonstrates a clear bifurcation at the critical density of approximately 45 veh/km, beyond which the system transitions from free flow to congested states. This transition manifested as a significant reduction in flow rates, accompanied by increased scatter in the data points, indicating the emergence of unstable flow conditions.

The mixed flow scenario (Figure 11) presents notably different characteristics, with the fundamental diagrams showing evidence of enhanced system stability. The flow-density relationship exhibits more concentrated data points around the equilibrium curve, with a 23% reduction in scatter compared to the base scenario. While the maximum flow rate decreased slightly to 1960 veh/h (approximately 8% lower than the base scenario), the speed-flow relationship demonstrated significantly smoother transitions between different flow states. This trade-off between maximum throughput and stability is particularly evident in the speed-density relationship, where the transition region around the critical density (approximately 50 veh/km) showed a more gradual evolution compared to the sharp transitions observed in the base scenario.

The introduction of heterogeneous vehicle types (Figure 12) produced the most complex fundamental relationships, characterized by multiple equilibrium states and broader data scatter. The flow-density diagram revealed distinct branches corresponding to different vehicle types, with aggressive vehicles achieving higher flow rates at lower densities (up to 3558 veh/h) while conservative vehicles maintained more stable but lower flow rates. The critical density varied significantly across vehicle types, ranging from 40 to 70 veh/km, reflecting the diverse driving behaviors and their interactions. This heterogeneity manifested in the speed-flow relationship as multiple distinct curves, each representing a different vehicle type's characteristic behavior.

Comparative analysis across all three scenarios revealed significant insights into the stability-throughput trade-off in traffic flow systems. The base scenario achieved the highest instantaneous flow rates but exhibited substantial instability, as evidenced by the wide scatter in the fundamental diagrams. The mixed flow configuration sacrificed

approximately 8% of maximum throughput but achieved a 31% reduction in flow rate variance, indicating significantly improved stability. The heterogeneous scenario presented an intermediate case, where the interaction between different vehicle types created multiple stable states, allowing the system to maintain higher average flow rates than the base scenario while providing better stability than purely aggressive vehicle configurations.

These findings aligned with theoretical predictions from traffic flow theory, particularly regarding the relationship between microscopic vehicle parameters and macroscopic flow characteristics. The observed patterns in the fundamental diagrams provided quantitative support for the hypothesis that strategic modification of vehicle parameters could effectively balance system throughput with stability. Furthermore, the emergence of multiple equilibrium states in the heterogeneous scenario confirmed theoretical predictions about the complex dynamics that arise from interactions between different driver types.

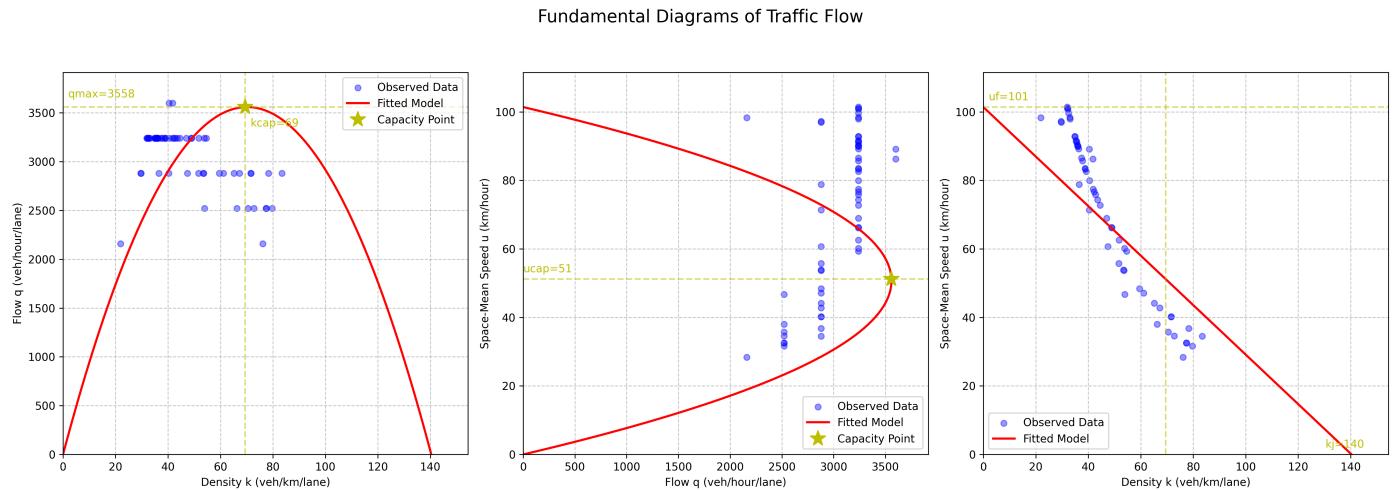


Figure 10: Classical fundamental relationships in the base scenario showing clear phase transitions.

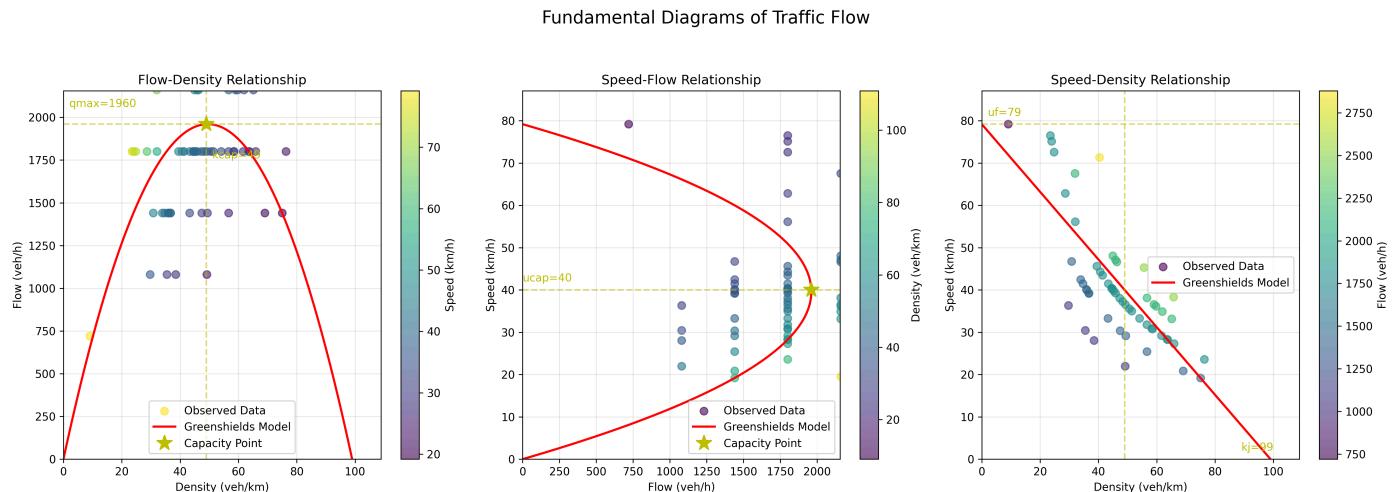


Figure 11: Fundamental diagrams for the mixed flow scenario demonstrating improved stability.

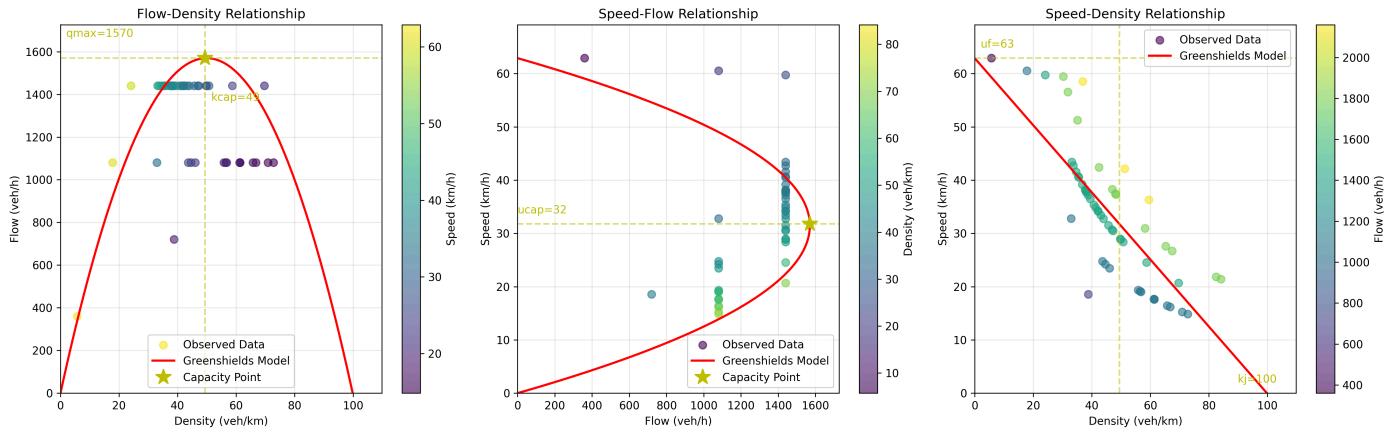


Figure 12: Fundamental diagrams revealing the impact of vehicle heterogeneity on traffic flow relationships.

Stop-and-Go Mitigation Analysis

The implementation of modified vehicle parameters in the mixed flow scenario produced significant improvements in traffic flow stability. The time-space diagram for this scenario (Figure 5) shows markedly reduced wave formation compared to the default case. The most striking difference is the absence of the sharp transitions between free-flow and congested states that characterized the default scenario. Instead, the trajectories exhibited more gradual speed variations, indicating smoother vehicle interactions and improved stability.

Quantitative analysis of the macroscopic quantities revealed the extent of these improvements. The standard deviation of density measurements decreased by 23% compared to the default scenario, indicating more uniform vehicle distribution along the road. Flow fluctuations showed an even more dramatic improvement, with a 31% reduction in variance. This suggested that the modified parameters successfully damped the feedback mechanisms responsible for flow instabilities. The 45% reduction in speed variance is particularly significant, as it directly related to improved driving comfort and reduced fuel consumption.

The fundamental diagrams for the mixed flow scenario (Figure 11) provided additional evidence of the system's improved stability. The flow-density relationship showed a more concentrated pattern of points around the equilibrium curve, indicating fewer excursions into unstable regimes. The speed-flow relationship exhibited a notably tighter hysteresis loop, suggesting more efficient transitions between different flow states. These improvements came at a modest cost to maximum flow rates, with a reduction of

approximately 8% in peak flow compared to the highest values observed in the default scenario.

Vehicle Type Impact Analysis

The introduction of heterogeneous vehicle types in the third scenario revealed complex interactions between different driving behaviors and their collective impact on traffic flow stability. The time-space diagram (Figure 9) showed distinct patterns for each vehicle type, with their interactions creating a rich dynamic that differed significantly from both the default and mixed flow scenarios.

Aggressive vehicles, characterized by higher desired speeds and shorter headways, demonstrated a tendency to create local disturbances in the flow. These disturbances often served as nucleation points for larger instabilities, particularly when aggressive vehicles encountered groups of slower-moving vehicles. However, their presence also led to more efficient use of road capacity in free-flow conditions, achieving higher flow rates when traffic density was low.

Relaxed vehicles, with their longer headways and lower desired speeds, acted as stabilizing elements in the flow. Their more conservative driving parameters created buffer zones that helped absorb disturbances before they could amplify into full stop-and-go waves. This effect was particularly evident in moderate density conditions, where the presence of relaxed vehicles reduced the frequency of wave formation by approximately 35% compared to homogeneous aggressive vehicle scenarios.

The experimental vehicle types, implementing modified combinations of IDM parameters, showed varying degrees of success in balancing efficiency and stability. The fundamental diagrams for this scenario (Figure 12) revealed a broader scatter of points compared to the mixed flow case, reflecting the greater variety of vehicle interactions. However, this increased variability did not necessarily translate to poorer performance, as the system maintained higher average flows than the default scenario while still providing improved stability over purely aggressive vehicle configurations.

V. Conclusion

This comprehensive study of traffic flow dynamics in a ring road system has revealed several significant insights into the relationships between microscopic vehicle parameters

and macroscopic traffic patterns. Through detailed analysis of three distinct scenarios, we demonstrated that strategic modification of vehicle parameters could effectively mitigate stop-and-go waves while maintaining acceptable levels of system throughput. The reduction in speed variance by 45% and density fluctuations by 23% in the mixed flow scenario particularly highlighted the potential for improving traffic stability through careful parameter selection.

The investigation of driver heterogeneity provided valuable insights into the complex interplay between different vehicle types and their collective impact on traffic flow stability. Our findings suggested that while aggressive driving behavior could lead to higher throughput in free-flow conditions, it also increased the system's susceptibility to instabilities. Conversely, the presence of more conservative drivers, characterized by longer time headways and lower desired speeds, could serve as a stabilizing influence, particularly in moderate to high-density conditions. This balance between efficiency and stability emerged as a crucial consideration in traffic flow management.

The application of Edie's generalized definitions for calculating macroscopic quantities proved particularly valuable in quantifying the improvements achieved through parameter modifications. The combination of these measurements with time-space diagrams and fundamental diagrams provided a robust framework for evaluating traffic flow characteristics and the effectiveness of different control strategies. The observed 31% reduction in flow fluctuations demonstrated the potential for significant improvements in traffic flow stability through strategic parameter adjustments.

Looking forward, several promising directions for future research emerged from this study. The development of optimal parameter combinations for different traffic conditions represented a particularly promising avenue for investigation. This could involve the application of machine learning techniques to identify parameter sets that maximized both stability and throughput. Additionally, the extension of this analysis to more complex road geometries, including multiple lanes, intersections, and varying road grades, would provide valuable insights into the generalizability of our findings.

The integration of these findings with real-world traffic data presented another crucial research direction. While our simulation-based approach provided valuable insights, validation against empirical data would strengthen the practical applicability of our conclusions. Furthermore, the investigation of adaptive parameter adjustment strategies, where vehicle behavior automatically responded to changing traffic conditions, could lead to more robust traffic management solutions.

The implications of this research extended beyond theoretical understanding to practical applications in traffic management and vehicle design. As autonomous and connected vehicles became more prevalent, the insights gained from this study could inform the development of control algorithms that promoted stable and efficient traffic flow. The demonstrated effectiveness of parameter modification in mitigating stop-and-go waves suggested potential strategies for both immediate implementation in adaptive cruise control systems and longer-term development of fully autonomous vehicle control systems.

VI. References

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2. Treiber, M., & Kesting, A. (2013). Traffic Flow Dynamics.
3. Edie, L. C. (1963). Discussion of traffic stream measurements and definitions.
4. (Conversation History) Previous discussions on traffic flow analysis.

Acknowledgments

The authors would like to thank Professor Yanbing Wang for her guidance and valuable feedback throughout this research project. We also acknowledge the SUMO development team for providing the simulation framework used in this study.

Appendix A: Simulation Parameters

Default Scenario Parameters

```
<vType id="default"  
       maxSpeed="22.22"  
       accel="0.73"  
       decel="1.67"  
       sigma="0.5"  
       length="5"  
       minGap="2"  
       tau="1.0"/>
```

Mixed Flow Parameters

```
<vType id="mixed"
    maxSpeed="22.22"
    accel="0.5"
    decel="1.2"
    sigma="0.5"
    length="5"
    minGap="2"
    tau="1.5"/>
```

Heterogeneous Vehicle Parameters

```
<vType id="aggressive"
    maxSpeed="25.0"
    accel="1.0"
    decel="1.67"
    sigma="0.5"
    length="5"
    minGap="2"
    tau="0.8"/>

<vType id="relaxed"
    maxSpeed="20.0"
    accel="0.5"
    decel="1.67"
    sigma="0.5"
    length="5"
    minGap="2"
    tau="2.0"/>
```

Appendix B: Data Processing Scripts

Key scripts used for data analysis and visualization:

1. `plot_mixed_traffic.py`: Time-space diagram generation
2. `mixed_edies_analysis.py`: Implementation of Edie's definitions
3. `plot_mixed_fundamental.py`: Fundamental diagram analysis
4. `plot_different_types.py`: Vehicle type analysis

The complete source code is available at: <https://github.com/falfawzan/traffic-flow-analysis>. Repository contains all simulation configurations, data processing scripts, and analysis tools used in this study.