# SUMO Simulation Study

## CEE598 Traffic Flow Theory

Raswanth Prasath S V

School of Sustainable Engineering and the Built Environment
Arizona State University

Spring 2025

# Contents

**1 Introduction** **1**
1.1 SUMO Overview . . . 1
1.2 Project Objectives . . . 1

**2 Simulation Setup** **1**
2.1 Network Definition (1k.net.xml) . . . 1
2.2 Simulation Settings (1k.sumocfg) . . . 1
2.3 Additional Elements (input_additional.add.xml) . . . 1
2.4 Vehicle Definitions (input_routes.rou.xml) . . . 2

**3 Default Simulation** **2**
3.1 Time-Space Diagram . . . 3
3.2 Observed Traffic Patterns . . . 3

**4 Macroscopic Quantities** **3**
4.1 Methodology . . . 4
4.2 Results . . . 4
4.3 Discussion . . . 4

**5 Loop Detector** **5**
5.1 Detector Configuration . . . 5
5.2 Fundamental Diagrams . . . 6

**6 Eliminating Stop-and-Go Traffic** **6**
6.1 Intelligent Driver Model (IDM) . . . 6
6.2 Methodology . . . 7
6.3 Results . . . 8
6.4 Alternative Approach . . . 10

**7 IDM Parameter Configurations** **11**
7.1 Simulation Setup . . . 12
7.2 Time-Space Diagrams . . . 12
7.3 Discussion . . . 13

# List of Figures


1 SUMO circle route Network . . . . . 2
2 Time-space diagram of vehicle trajectories in the default simulation. . . . 3
3 Time-space diagram of vehicle trajectories with speed. . . . . 3
4 (i)Density heatmap (veh/km) over space and time(Top) (ii)Flow heatmap (veh/h) over space and time(middle). (iii) Speed heatmap (km/h) over space and time (bottom) . . . . . 5
5 Detector (det_0) (i) Flow vs. density (ii) Speed vs. density (iii) Speed vs. flow . . . . . 6
6 Detector (det_1) (i) Flow vs. density (ii) Speed vs. density (iii) Speed vs. flow . . . . . 6
7 Time-space diagrams before and after modification. . . . . 8
8 Velocity-Time diagrams before and after adding a smoother vehicle. . . . 9
9 Flow patterns before and after adding a smoother vehicle. . . . . 9
10 Velocity standard deviation comparison before and after adding a smoother vehicle. . . . . 9
11 Time-space diagrams . . . . . 10
12 Flow and Velocity st. dev. patterns after adding an autonomous vehicle. 10
13 Velocity-Time diagrams after adding an autonomous vehicle. . . . . 11
14 IDM parameters (theoretical) . . . . . 12
15 Time-space diagram for *aggressive* configuration. . . . . 12
16 Time-space diagram for *exp_rspsv* configuration. . . . . 13
17 Time-space diagram for *relaxed* configuration. . . . . 13
18 Time-space diagram for *exp_dfsv* configuration. . . . . 13


# List of Tables


1 Traffic flow metrics for the default scenario . . . . . 9
2 Traffic flow metrics for modified scenario . . . . . 10
3 Traffic flow metrics for autonomous vehicle scenario . . . . . 11
4 IDM Parameter Configurations for Different Vehicle Types . . . . . 12

# 1 Introduction

## 1.1 SUMO Overview

"Simulation of Urban MObility" (SUMO) is an open-source, microscopic traffic simulation package designed to model large-scale traffic networks with high fidelity [1]. Developed by the Institute of Transportation Systems at the German Aerospace Center, SUMO enables detailed simulation of individual vehicle movements, traffic signals, and road network dynamics. It supports intermodal scenarios, including pedestrians, and is equipped with tools like `netedit` and `sumo-gui` for scenario creation and visualization. This project uses SUMO to analyze traffic behavior in a controlled ring-road environment.

## 1.2 Project Objectives

This project uses a simple ring-road scenario to explore traffic stability, where vehicles circulate in a closed circle loop. The objectives include running a default simulation, calculating macroscopic traffic quantities, implementing a loop detector, modifying vehicle behavior to mitigate stop-and-go traffic, and examining the effects of different driver parameter configurations.

# 2 Simulation Setup

This section describes the key files used in the ring-road traffic simulation experiment.

## 2.1 Network Definition (1k.net.xml)

The `1k.net.xml` file defines the physical structure of the circular track used in the simulation. The network file has a closed single-lane ring road with a circumference of approximately 1000.76 meters. Maximum speed on all lanes is 100 m/s , allowing vehicles to reach their desired speed.

## 2.2 Simulation Settings (1k.sumocfg)

The `1k.sumocfg` file controls the simulation parameters:

- **Input Files:** Specifies the network file, route file, and additional file
- **Time Settings:** Sets simulation duration to 600 seconds with a step length of 0.1 seconds for high-resolution trajectory recording
- **Output:** Configures Floating Car Data output (`output_fcd.xml`) to record vehicle positions and speeds
- **Constraints:** Limits maximum vehicle count to 200 and maximum departure delay to 2 seconds

## 2.3 Additional Elements (input_additional.add.xml)

The `input_additional.add.xml` file defines critical simulation components. It creates a route named "circle" that uses edges "a b a" and ensures vehicles continue circulating on the ring throughout the simulation. An induction loop detector is placed at position 50m on lane `a_0` that records traffic data every 30 seconds.

### 2.4 Vehicle Definitions (input_routes.rou.xml)

The `input_routes.rou.xml` file specifies the vehicles and traffic flow. It defines four different driver profiles using the Intelligent Driver Model (IDM) and creates a flow of 50 vehicles with `aggressive` type, departing between 0-1 seconds.

## 3 Default Simulation

In this section, we execute the default circle-road simulation for 600 seconds without modifying any configuration files, plot the time-space diagram, and analyze the resulting traffic patterns.

The initial setup consisted of the launching of 50 vehicles of the "aggressive" type into the simulation along the "circle" route. The vehicles are added between time 0 and 1 second, with their departure times spread evenly across this interval. The following line in `.rou.xml` file that describes the vehicle flows:

```
<flow id="flow1" type="aggressive" route="circle" begin="0" end="
    ↪ 1" number="50" departPos="last" departSpeed="4.08"/>
```

Each vehicle is placed at the last free position on the starting edge of the "circle" route, ensuring they are distributed without overlapping, likely spreading them along the ring road. They all begin moving at an initial speed of 4.08 m/s, though their "aggressive" type might allow them to accelerate to a higher maximum speed (e.g., 44.4 m/s) depending on traffic conditions.

```
<vType id="aggressive" carFollowModel="IDM" maxSpeed="44.4"
    ↪ minGap="1" accel="2" decel="3" tau="0.8" length="4.5"/>
```

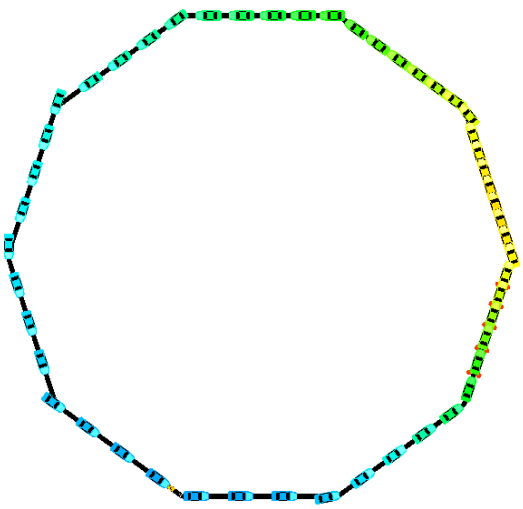


Figure 1: SUMO circle route Network

The simulation duration is set to 600 seconds, and trajectory data is collected using SUMO's `fcd-output` option, which records vehicle positions at each time step.

### 3.1 Time-Space Diagram

The time-space diagram (Figure 2 and Figure 3 ) plots time (x-axis, 0 to 600 seconds) against the position on the ring road. Each line represents a vehicle's trajectory, with the slope indicating its speed. The diagram reveals periodic stop-and-go waves forming after 30 seconds, with vehicles slowing and accelerating in clusters.

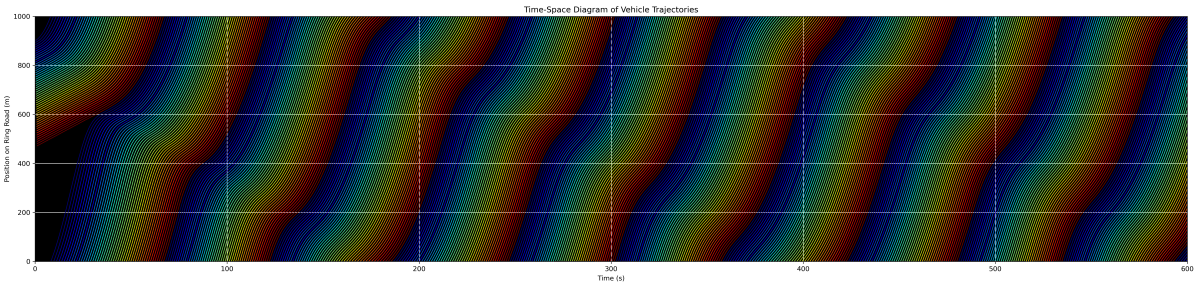



Figure 2: Time-space diagram of vehicle trajectories in the default simulation.

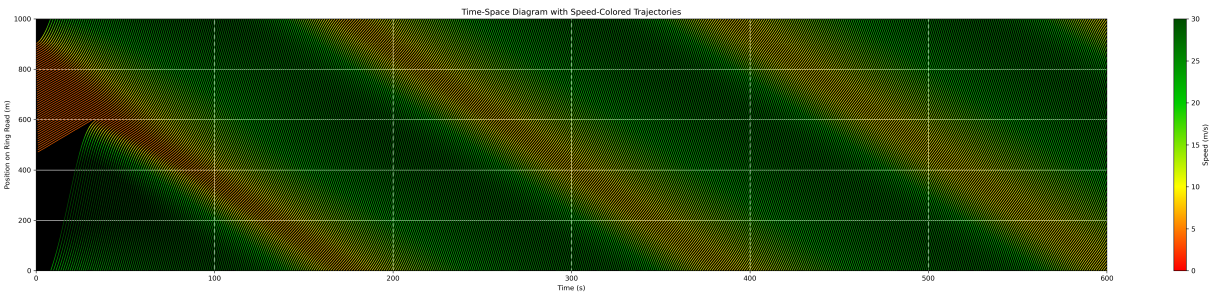



Figure 3: Time-space diagram of vehicle trajectories with speed.

### 3.2 Observed Traffic Patterns

The traffic pattern in this ring road network begins with a free-flow state, where 50 vehicles move uniformly at 4.08 m/s with even spacing. As the simulation progresses, the high density (50 veh/km) and aggressive IDM parameters (tau = 0.8 s, s_0 = 1 m) introduce instabilities. Small speed fluctuations amplify via a feedback mechanism, forming stop-and-go waves that propagate upstream at 4–5 m/s. These waves cause speed oscillations from 0 to 25 m/s, reflecting an unstable flow consistent with theoretical and empirical traffic dynamics at densities above 25 veh/km/lane. This suggests an unstable traffic flow, likely due to high vehicle density triggering perturbations that propagate around the ring.

## 4 Macroscopic Quantities

This section implements Edie's definitions to compute macroscopic traffic quantities—density, speed, and flow—from the default simulation trajectories, using discretization windows of 10 seconds and 10 meters.

## 4.1 Methodology

Edie's generalized definitions provide a robust framework for calculating traffic flow variables in a space-time region $A$ with area $|A| = \Delta t \cdot \Delta x$ (here, $\Delta t = 10$ s, $\Delta x = 10$ m):

- Density $k = \frac{T(A)}{|A|}$, where $T(A)$ is the total time spent by vehicles in $A$.
- Flow $q = \frac{D(A)}{|A|}$, where $D(A)$ is the total distance traveled in $A$.
- Speed $v = \frac{D(A)}{T(A)}$, if $T(A) > 0$.

To implement this method, we processed the SUMO Floating Car Data (FCD) output to track vehicle trajectories around the 1000.76 m ring road. The computational procedure involved:

1. Unwrapping vehicle positions to account for multiple loops around the ring
2. Discretizing the space-time domain into a 60×100 grid (600s × 1000m with 10s × 10m cells)
3. Calculating $T(A)$ and $D(A)$ for each cell by tracking the time spent and distance traveled by each vehicle
4. And calculating $k$, $q$, and $v$ using Edie's formulas, converting to standard traffic units (veh/km, veh/h, km/h)

## 4.2 Results

Figures 4 present heatmaps of density, flow, and speed, respectively, with time on the x-axis and position on the y-axis.

## 4.3 Discussion

The density heatmap (Figure 4) shows diagonal bands of higher vehicle concentration moving backward through traffic. These represent stop-and-go waves propagating upstream at approximately 5 m/s, a typical speed for congestion shockwaves.

The correlation between the three visualizations confirms fundamental traffic flow relationships:

- Areas of high density correspond precisely to low speeds and reduced flow, comparing (i) and (ii) in Figure 4
- Regions between congestion waves show moderate density, high speeds, and maximum flow
- The diagonal patterns in all three heatmaps travel with nearly identical wave speeds but in the opposite direction of traffic flow

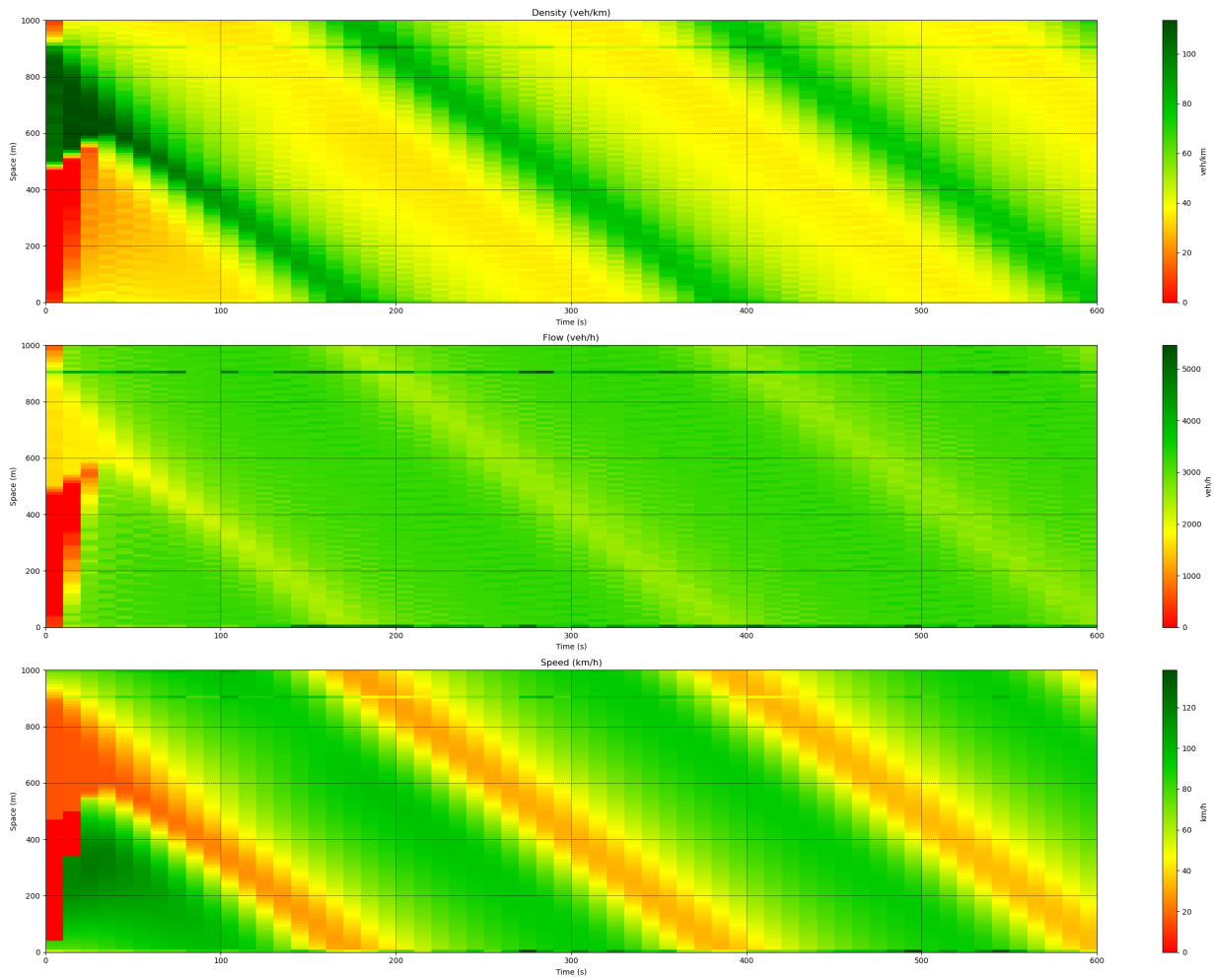



Figure 4: (i)Density heatmap (veh/km) over space and time(Top) (ii)Flow heatmap (veh/h) over space and time(middle). (iii) Speed heatmap (km/h) over space and time (bottom)

# 5 Loop Detector

An E1 induction loop detector is added to the ring-road network to collect data for plotting fundamental diagrams relating flow, density, and speed.

## 5.1 Detector Configuration

Two detectors is defined in an additional file (`.add.xml`) at positions 50 m and 250 on lane `a_0` along the ring road:

```
<e1Detector id="det_0" lane="a_0" pos="50" freq="8" file="
    ↪ output_detector.out.xml" />
<e1Detector id="det_1" lane="a_0" pos="250" freq="15" file="
    ↪ output_detector1.out.xml" />
```

Detector (det_0) and (det_1) records flow (vehicles/s), speed (m/s), and occupancy every 8 and 15 seconds, respectively, over the 600-second simulation.

It is programmed to record flow, speed and occupancy metrics throughout the 600-second simulation duration. The collected data is output to the file `output_detector.out.xml` and `output_detector1.out.xml` for subsequent analysis and visualization.

## 5.2 Fundamental Diagrams

Using detector data, flow $q$ is directly measured, speed $v$ is averaged per interval, and density $k$ is estimated as $k = q/v$. Results are plotted in Figures 6 and .

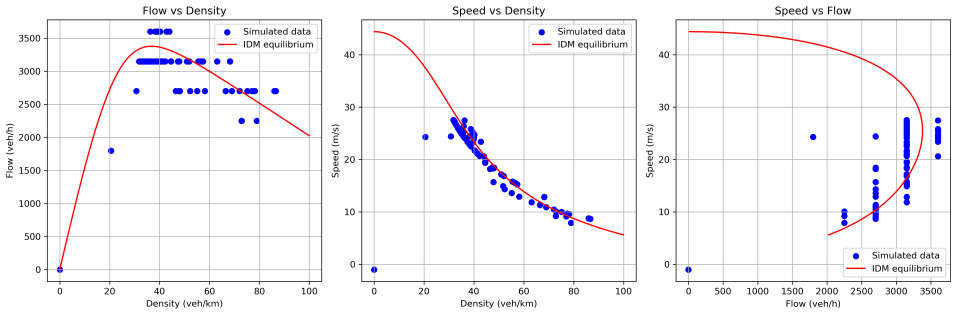



Figure 5: Detector (det_0) (i) Flow vs. density (ii) Speed vs. density (iii) Speed vs. flow

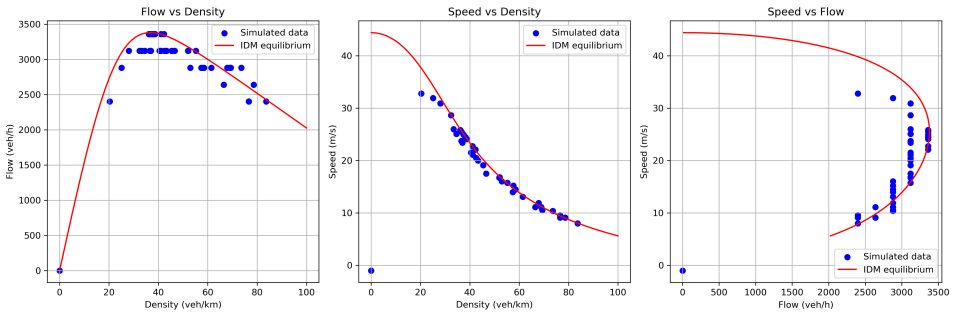



Figure 6: Detector (det_1) (i) Flow vs. density (ii) Speed vs. density (iii) Speed vs. flow

# 6 Eliminating Stop-and-Go Traffic

This section modifies one vehicle's IDM parameters to eliminate stop-and-go traffic, evaluates the results, and explores trade-offs and alternatives.

## 6.1 Intelligent Driver Model (IDM)

The Intelligent Driver Model (IDM) is a microscopic traffic flow model that describes how vehicles accelerate and decelerate based on their surroundings. This car-following model is widely used in traffic simulations due to its realistic representation of driver behavior through a manageable set of parameters. In this report, we examine how different IDM parameter configurations affect traffic patterns in a circular road simulation implemented in SUMO.

The IDM acceleration function is given by:

$$\dot{v} = a\left[1 - \left(\frac{v}{v_0}\right)^{\delta} - \left(\frac{s^*(v,\Delta v)}{s}\right)^2\right] \tag{1}$$

The key parameters in this model are:

- $v_0$: desired velocity in free traffic
- $a$: the maximum vehicle acceleration
- $b$: comfortable braking deceleration (positive)

where $s^*$ is defined as:

$$s^*(v,\Delta v) = s_0 + vT + \frac{v\Delta v}{2\sqrt{ab}} \tag{2}$$

where

- $s_0$: minimum spacing from the preceding vehicle
- $T$: desired time headway (tau)
- $\Delta v = v$- $v_l$: speed difference to the leading vehicle (where $v_l$ is leader's speed)
- $v\Delta v/2\sqrt{ab}$: dynamic term that adjusts the desired distance based on relative motion

## 6.2 Methodology

One of the key concepts for flow stabilization involves incorporating a subset of vehicles that maintain smooth driving patterns relative to traffic conditions. One effective approach is to have these vehicles follow the average speed of vehicles ahead—driving faster than the average before encountering stop-and-go waves and slower than average during the waves. By maintaining this average speed, a vehicle covers the identical distance in the same timeframe but with significantly reduced acceleration and braking [2].
But we also have to consider that very small values of $b$ make the model overly sensitive, demanding huge gaps and triggering excessive braking in mild situations while failing to reflect practical driving behaviour. As $b$ shrinks, $s_0$ increases, this would demand excessively large gaps to the vehicle ahead, far beyond typical traffic conditions. [3]
With this concept in mind, we implement a smoother IDM model vehicle.

To stabilize traffic, we modify the time headway (`tau`) of one vehicle in `circles.rou.xml`:

```
<vType id="smoother" carFollowModel="IDM" maxSpeed="25" minGap="2
   ↪ " accel="1" decel="1" tau="2.5" length="4.5" />

<vehicle id="veh_0" type="smoother" route="circle" depart="5"
   ↪ departPos="last" departSpeed="4.08" />
```

To dissipate these waves, the approach was to introduce a single "smoother" vehicle with modified IDM parameters designed to dampen oscillations. The parameters were set as follows:

- minGap=2 m, to maintain a safer distance and absorb fluctuations.
- accel=1 m/s$^2$, to limit rapid acceleration and prevent overreaction.
- decel=1 m/s$^2$, for smoother deceleration.

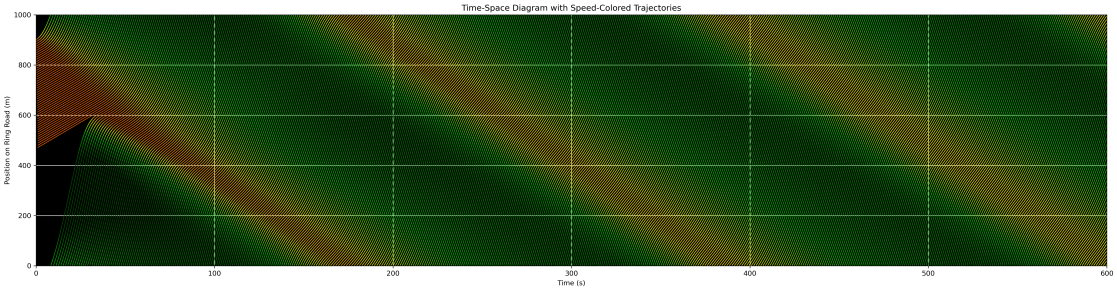
- tau=2.5 s, much larger than 0.8 s, to increase the desired time headway, promoting stable following behavior.
- length=4.5 m, consistent with other vehicles for uniformity.

This vehicle was added to the simulation by defining a new vType in the .rou.xml file and including it as an individual vehicle with the route "circle," departing at time 5 with departPos="last" and departSpeed="4.08" m/s. This resulted in a total of 51 vehicles, with 50 aggressive and one smoother vehicle.

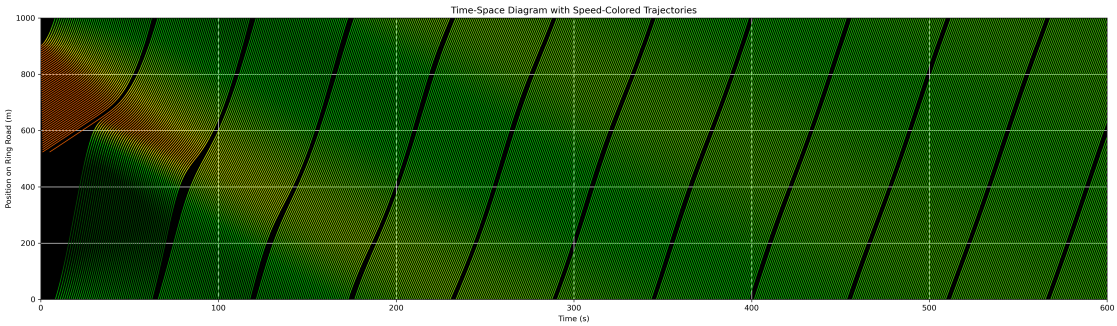
This increases the following distance, potentially damping oscillations. The rationale is that a vehicle with larger gaps and slower reactions can act as a shock absorber, preventing the amplification of speed differences that lead to wave formation.

## 6.3 Results

Figure 11 compares the default and modified time-space diagrams.



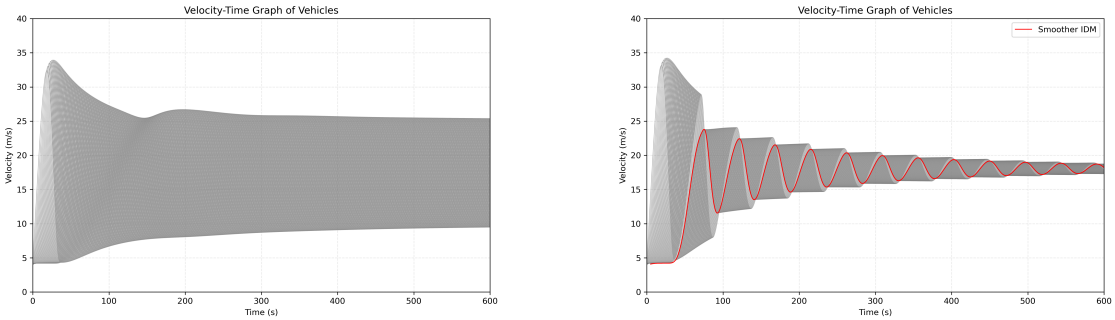

(a) Default scenario.




(b) Modified scenario.

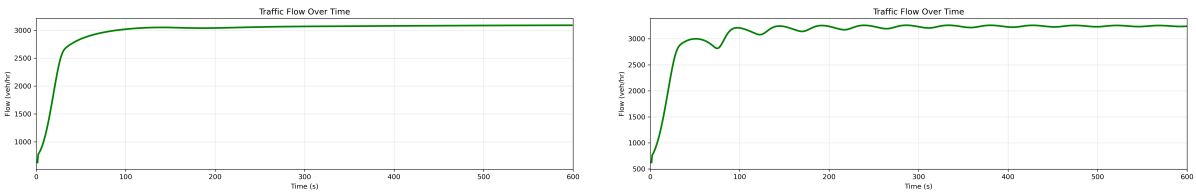
Figure 7: Time-space diagrams before and after modification.

The modified scenario shows smoother trajectories with no stop-and-go waves, indicating successful stabilization. Figure 13 shows velocity profile and the traffic state is quantified in each interval in Table 1 and Table 3.



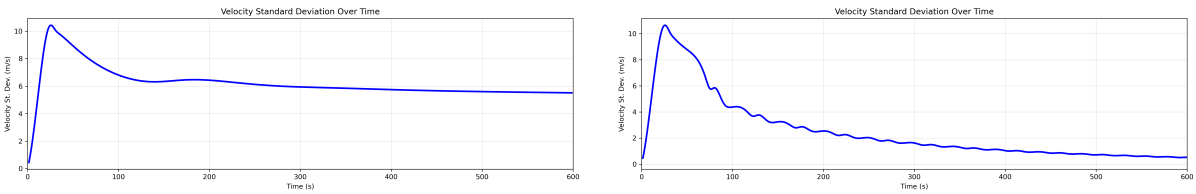

(a) Default scenario. (b) Modified scenario.

Figure 8: Velocity-Time diagrams before and after adding a smoother vehicle.




(a) Default scenario. (b) Modified scenario.

Figure 9: Flow patterns before and after adding a smoother vehicle.




(a) Default scenario. (b) Modified scenario.

Figure 10: Velocity standard deviation comparison before and after adding a smoother vehicle.

| **Time (s)** | **Velocity st. dev. (m/s)** | **Flow (veh/hr)** |
|---|---|---|
| 0 | 7.69 | 2494 |
| 100 | 6.44 | 3043 |
| 200 | 6.15 | 3058 |
| 300 | 5.85 | 3074 |
| 400 | 5.67 | 3083 |
| 500 | 5.56 | 3089 |

Table 1: Traffic flow metrics for the default scenario

Velocity standard deviation indicates the presence of these waves. For example, a low value less than 2.5 m/s is considered as smoother, more uniform traffic flow. In the default scenario, velocity standard deviation remains high (5.56 m/s) even after 500 seconds,

| Time (s) | Velocity st. dev. (m/s) | Flow (veh/hr) |
|---|---|---|
| 0 | 7.03 | 2572 |
| 100 | 3.30 | 3185 |
| 200 | 1.98 | 3225 |
| 300 | 1.29 | 3237 |
| 400 | 0.87 | 3242 |
| 500 | 0.61 | 3245 |

Table 2: Traffic flow metrics for modified scenario

indicating persistent stop-and-go waves and traffic instability. In contrast, the modified scenario with a single stabilizer vehicle shows velocity standard deviation reaching 0 m/s by 400 seconds, demonstrating complete wave dissipation.

While initial flow in the modified scenario was lower (2457 veh/hr vs. 2494 veh/hr), once stability was achieved, flow increased substantially to 3245 veh/hr, exceeding the default scenario's 3089 veh/hr.

## 6.4 Alternative Approach

An alternative approach could be to add an autonomous vehicle as described in [2]. Using the TraCI (Traffic Control Interface) library.

Here we have implemented a simplified version of the FollowerStopper logic to dynamically control the autonomous vehicle's speed based on real-time gap ($\Delta x$) and velocity difference ($\Delta v$). We almost got similar results for the smoother vehicle, this shows that the autonomous vehicle can smoothen out the traffic waves.

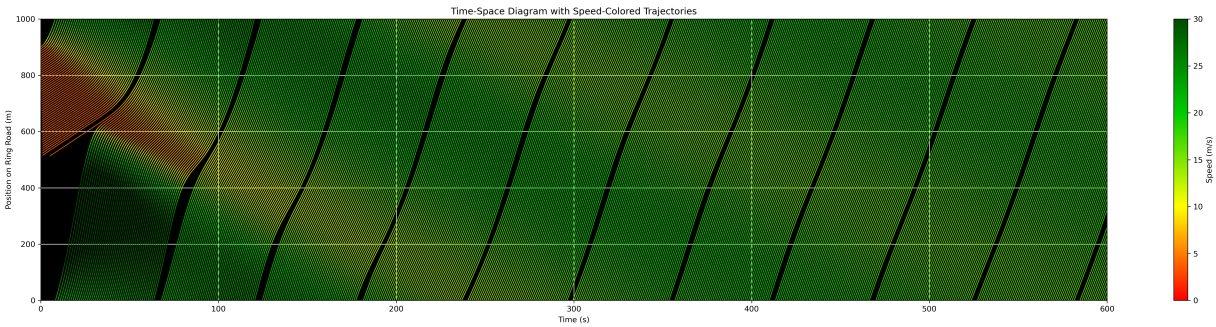
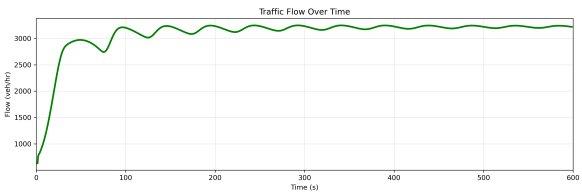
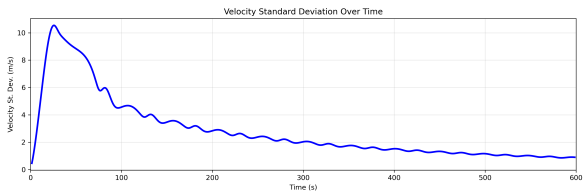



Figure 11: Time-space diagrams .




(a) Traffic Flow over time




(b) Velocity Standard Deviation over time

Figure 12: Flow and Velocity st. dev. patterns after adding an autonomous vehicle.

| Time (s) | Velocity st. dev. (m/s) | Flow (veh/hr) |
|---|---|---|
| 0 | 7.08 | 2550 |
| 100 | 3.62 | 3149 |
| 200 | 2.38 | 3193 |
| 300 | 1.71 | 3208 |
| 400 | 1.28 | 3215 |
| 500 | 0.98 | 3219 |

Table 3: Traffic flow metrics for autonomous vehicle scenario

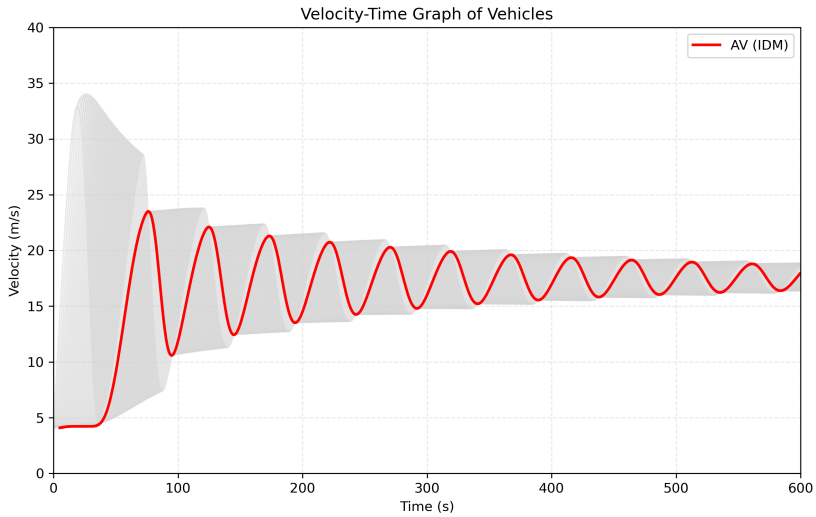



Figure 13: Velocity-Time diagrams after adding an autonomous vehicle.

# 7 IDM Parameter Configurations

Four vehicle type configurations—`aggressive`, `relaxed`, `exp_rspsv` and `exp_dfsv` were tested —by modifying the flow in `circles.rou.xml`, plotted time-space diagrams, and discussing IDM parameter impacts. These IDs categorize distinct driving behaviors for use in a traffic simulation:

- **aggressive:** An aggressive driver who drives fast, follows closely, and reacts quickly (which were the default initial scenario in our case).
- **exp_rspsv:** An experienced and responsive driver with balanced, cautious tendencies.
- **relaxed:** A relaxed or cautious driver who prioritizes safety and comfort.
- **exp_dfsv:** An experienced and defensive driver who maintains larger gaps and drives smoothly.

Table 4: IDM Parameter Configurations for Different Vehicle Types

| **Parameter** | **Aggressive** | **exp_rspsv** | **Relaxed** | **exp_dfsv** |
|---|---|---|---|---|
| maxSpeed $v_0$(m/s) | 44.4 | 33 | 22 | 33 |
| minGap $s_0$ (m) | 1 | 2 | 4 | 4 |
| accel $a$(m/s$^2$) | 2 | 2 | 1 | 1.5 |
| decel $b$ (m/s$^2$) | 3 | 1.5 | 2.5 | 1.5 |
| tau $T$(s) | 0.8 | 1.5 | 2 | 2 |

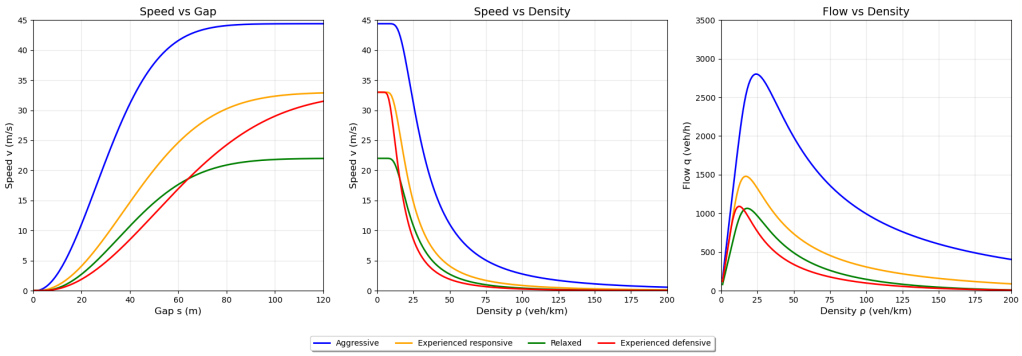



Figure 14: IDM parameters (theoretical)

## 7.1 Simulation Setup

Four vehicle types are defined with distinct IDM parameters:

- **aggressive**: maxSpeed=44.4, minGap=0.1, accel=2, decel=3, tau=0.8
- **relaxed**: maxSpeed=22, minGap=4, accel=1, decel=2.5, tau=2
- **exp_rspsv**: maxSpeed=33, minGap=2, accel=2, decel=1.5, tau=1.5
- **exp_dfsv**: maxSpeed=33, minGap=4, accel=1.5, decel=1.5, tau=2

Each simulation runs for 600 seconds with the updated flow type.

## 7.2 Time-Space Diagrams

Figures 15, 16, 17, and 18 show the trajectories for each configuration.

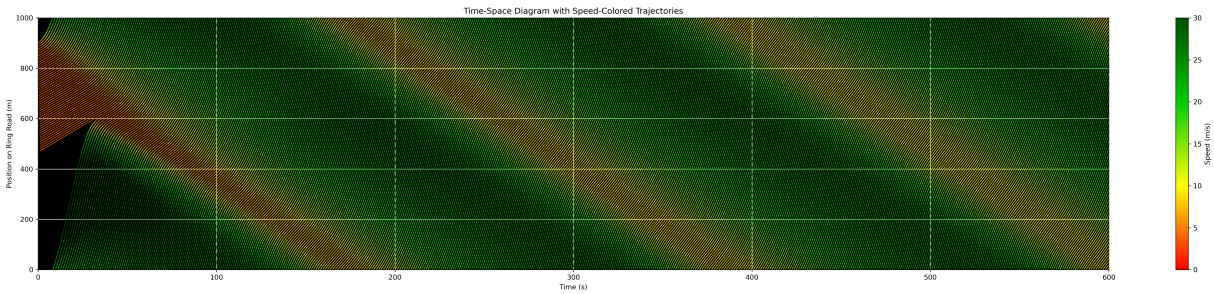



Figure 15: Time-space diagram for *aggressive* configuration.

Figures 15 show an initial traffic jam (0–100 s) with low speeds (red/yellow, 0–10 m/s). Vehicles then reach high speeds (green, 30 m/s) in a free-flow phase (200–600 s).

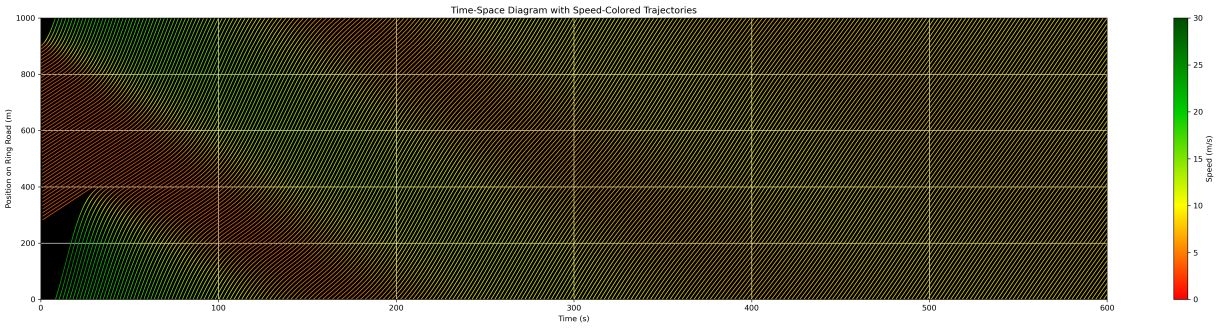



Figure 16: Time-space diagram for *exp_rspsv* configuration.

Figures 16 shows stable, free-flowing traffic with speeds of 10–25 m/s (yellow to green). Trajectories are parallel and evenly spaced, showing no significant congestion.

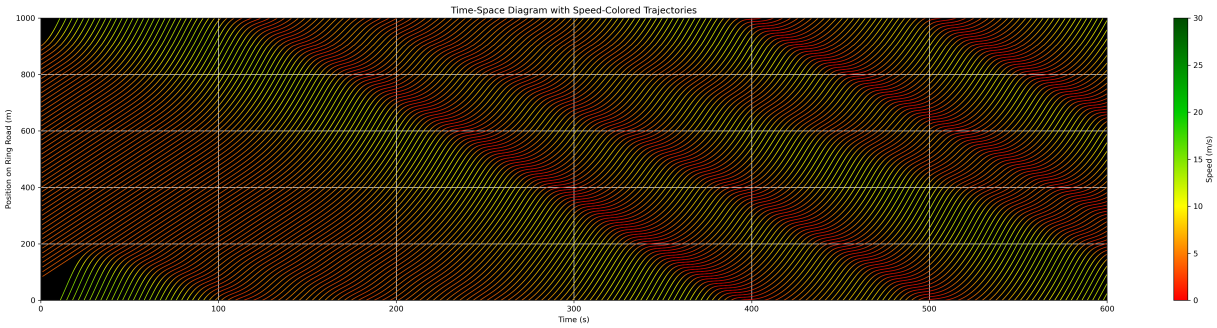



Figure 17: Time-space diagram for *relaxed* configuration.

Figures 17 exhibits significant congestion with stop-and-go waves throughout (0–600 s). Trajectories alternate between red (0 m/s) and light yellow (15–20 m/s), indicating persistent instability.

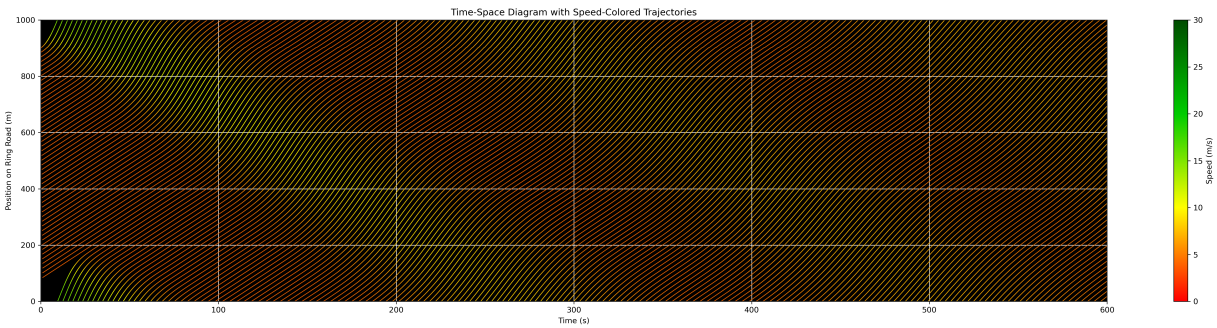



Figure 18: Time-space diagram for *exp_dfsv* configuration.

In figures 18, it starts with the smooth flow (0–50 s, yellow/green, 10–20 m/s), followed by traffic jams (50–600 s, red/orange, 0–10 m/s).

## 7.3 Discussion

The time-space diagrams reveal distinct traffic patterns for each vehicle configuration, highlighting the impact of IDM parameters on traffic stability and flow characteristics.

Treiber's simulation demonstrates that traffic instabilities, like stop-and-go waves, emerge from small perturbations at high densities. In our case, the 50 vehicles/km density exceeds typical critical thresholds (20–30 vehicles/km), making flow stability dependent on IDM parameters. The `aggressive` settings mirror Treiber's [4] high-speed scenarios where close following triggers jams that resolve quickly. The `relaxed` configuration reflects unstable flow patterns with persistent waves due to cautious driving that amplifies disturbances. Meanwhile, the balanced `exp_rspsv` parameters achieve the stable flow that Treiber identifies as possible with optimized parameter combinations.

The parameter sensitivity analysis reveals several key insights:

- **Maximum Speed:** Higher values enable faster free-flow speeds and accelerate jam dissipation, while lower values restrict throughput and prolong congestion.
- **Minimum Gap:** Smaller values increase density and jam risk but enhance recovery potential, while larger values reduce density but can amplify wave propagation.
- **Time Headway (tau):** Shorter values improve responsiveness and throughput while reducing wave amplitude; longer values delay reactions and can exacerbate instabilities.
- **Acceleration:** Higher values expedite recovery from slowdowns; lower values prolong the transition back to free flow.
- **Deceleration:** Higher values allow rapid braking to manage close-following situations; lower values promote smoother speed adjustments but may be insufficient to prevent cascading slowdowns.

These findings highlight the delicate balance required in car-following model parameterization. The optimal configuration depends on the specific traffic conditions and desired outcomes, whether prioritizing stability, throughput, or safety. The remarkable stability achieved by the `exp_rspsv` configuration suggests that moderate, balanced parameter values may offer the most robust performance across varying traffic densities.

# References

[1] SUMO Documentation: https://sumo.dlr.de/docs/index.html.

[2] Stern, Raphael E., et al. "Dissipation of Stop-and-go Waves via Control of Autonomous Vehicles: Field Experiments." ArXiv, 2017, https://doi.org/10.1016/j.trc.2018.02.005.

[3] Treiber, M., & Kesting, A. (2013). Traffic flow dynamics. Traffic Flow Dynamics: Data, Models and Simulation, Springer-Verlag Berlin Heidelberg Chapter 11.

[4] Martin Treiber's microsimulation tool https://www.traffic-simulation.de/ring.html.

[5] Project files: https://github.com/Raswanth-Prasath/SUMO-Simulation.