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HetroTraffSim: A Simulator for Heterogeneous Traffic Flow

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Abstract

Traffic simulation software (TSS) is employed for planning, designing, and managing road networks. Among existing TSS, only SUMO and HETROSIM can be used for heterogeneous traffic. The objective of this work is to develop new software for heterogeneous traffic simulation which is effective and efficient. This is motivated by the fact that traffic in developing countries is typically heterogeneous. The HetroTraffSim TSS was developed using Unity3D and is based on a recently developed macroscopic traffic flow model. A 360 m section of University Road which is a two-lane arterial road in Peshawar, Pakistan, is used to evaluate the performance using real traffic data. The results obtained show that an increase in density decreases the velocity. Further, HetroTraffSim can be used to characterize and predict heterogeneous traffic behavior.

Keywords: *traffic simulation software, flow, density, velocity, Unity3D, raycasting, heterogeneous traffic.*

1. Introduction

The percentage of the world population which is urban will increase to 64% and 86% for developing and developed countries, respectively, by 2050 [1]. This rapid urbanization creates significant challenges for future smart cities. One of these is urban mobility. Inefficient mobility results in traffic congestion, accidents, increased pollution, degraded quality of life, increased travel time, and lower productivity. In humans, this creates cardiovascular, respiratory, stress, fatigue, and psychological issues [2]. Traffic simulation software (TSS) can be employed for planning, designing, and managing urban road networks to alleviate these problems.

The goal of TSS is to predict traffic behavior for efficient road network management by traffic engineers. They are based on mathematical traffic models and have features such as 3D visualization and user-friendly GUIs. TSS such as PTV Vissum, Paramics, and Aimsun has been developed for homogenous traffic [3]. However, only SUMO and HETROSIM can be used for heterogeneous traffic [3]. Both are based on microscopic traffic flow models. However, they have serious drawbacks that limit their usefulness in predicting traffic behavior. HetroTraffSim can simulate only a few types of vehicles with fixed and similar attributes. Further, only simple road networks can be modeled so practical scenarios such as bottlenecks and intersections are not possible [4]. SUMO can only simulate heterogeneous traffic with lane discipline, but this is often not the case, particularly in developing countries.

Heterogeneous traffic behavior typically involves little or no lane discipline with both motorized and non-motorized vehicles such as cars, buses, trucks, motorbikes, three-wheelers, and animal\human driven carts. Further, lane markings are either absent or have inconsistent widths. Pedestrians also affect traffic flow and several models have been developed to determine their impact [5]. Existing pedestrian models include cellular automaton, social force, and multi-agent models [6]. The proposed TSS called HetroTraffSim has been developed to simulate heterogeneous traffic flow using a macroscopic traffic flow model. It has been developed based on the following objectives:

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1. provide TSS for heterogeneous traffic flow,
2. allow implementation flexibility over a wide range of parameters, and
3. Overcome the shortcomings of existing TSS by allowing complex and realistic environments with a variety of user features.

The proposed TSS has been developed with Unity3D using a second-order macroscopic traffic flow model [7]. A user can select the road length\width, number\density of vehicles, and minimum\maximum traffic flow, velocity, and time. The average velocity and density, traffic flow, and time are outputs. HetroTraffSim is evaluated using a 360 m section of University Road, Peshawar, Pakistan, which has two lanes and a width of 8.85 m.

The rest of this paper is organized as follows. Section 2 presents the related work and the HetroTraffSim framework is given in Section 3. Results to illustrate the proposed TSS are presented and discussed in Section 4. Finally, some concluding remarks are given in Section 5.

2. Related work

TSS plays a significant role in planning, designing, and managing road networks. PTV Vissim was used in [8] to analyze heterogeneous traffic at an intersection in Chennai, India. The methodology involved data collection, PTV Vissim configuration, sensitivity analysis, PTV Vissim calibration, and validation. Traffic parameters such as volume, composition, speed, and signal timing were extracted from two hours of peak time data. Seven types of driver behavior and four desired acceleration values were considered. It was shown that at the first sensitivity level, analysis of variance (ANOVA) and elementary effects (EE) are effective in determining the most important parameters. At the second sensitivity level, EE provides better results.

In [9], a simulator was developed using Unity3D to investigate driver behavior in heterogeneous traffic on roads in India. The emotions (frustration\anger) of over 30 participants were determined under three conditions: no lanes, lane-changing at certain points, and lanes separated by solid barriers. It was concluded that the time taken to navigate the road was the smallest with no lanes and the highest with lanes separated by solid barriers. Further, frustration/anger was observed in 73% of the participants because of not being able to change lanes when there were slow-moving vehicles.

A cellular automata (CA) model was proposed in [10] to study heterogeneous traffic behavior. The vehicle types considered were car, truck, bus, and two- and three-wheelers with the parameters speed, acceleration, and dimensions. The simulation results were validated using real data.

In [11], a Unity3D-based simulator was developed for heterogeneous traffic. Navmesh was used for the movement of vehicles and pedestrians, and raycasting was employed to improve dynamics. Detailed motion parameters can be input such as the ability to make left and/or right turns. The output parameters include the number of vehicles and pedestrians, number of stopped and in-motion vehicles, wait time at traffic signals, and average distance traveled per minute. It was determined that traffic signal wait time has a significant impact on traffic flow.

The HETROSIM simulator for heterogeneous traffic was developed in [12]. Real data from three roads in India was used for calibration and validation. Traffic parameters considered include vehicle dimensions, speed, headway, and acceleration, and both 2-lane and 4-lane roads can be simulated. The output includes the number of passenger car units (PCU) per hour. However, driver behavior is not considered in HETROSIM.

The limitations of existing TSS for heterogeneous traffic motivated the development of HetroTraffSim. It has the following capabilities:

1. Heterogeneous traffic without lane discipline can be simulated.
2. Real data can be incorporated.
3. Parameters such as vehicle dimensions, maximum\minimum velocity, vehicle instantiation time, road length and width, and traffic density can be input.
4. A graphical user interface (GUI) and 3D visualization are provided which are more user-friendly than in SUMO and HETROSIM.

3. Simulation framework

HetroTraffSim was developed using Unity3D and C# scripts to simulate heterogeneous traffic flow behavior. The block diagram in Figure 1 shows that parameters such as road length\width, initial traffic density, time, and minimum\maximum velocity can be input via the GUI. A mathematical traffic flow model is employed as explained in Section 3.2. The simulator provides density, velocity, and flow for every road segment as outputs. The results are stored on a cloud platform to allow quick access for analysis.

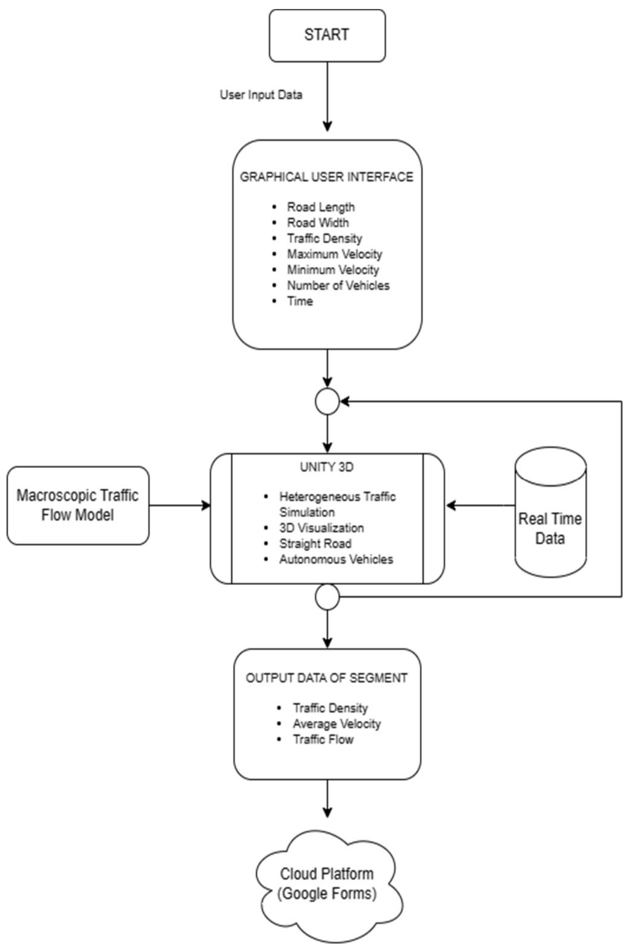

Figure 1. Block diagram of the HetroTraffSim framework.

3.1. Unity3D

Unity3D was chosen to develop HetroTraffSim because it is user-friendly and has been shown to provide realistic results. It provides excellent functionality with a range of parameters and post-processing capabilities. This allows users to create 2D\3D simulations using C# scripts with drag-and-drop functionality [13]. Further, cloud-based project sharing and development enables multiple developers to work together for a fast, secure, and reliable workflow.

3.1.1. Road infrastructure

Realistic road infrastructure is important for accurate traffic simulation. In HetroTraffSim, EasyRoads3D [14] is employed because of its simplicity to build a realistic road network with high-resolution textures. The length and width of the road can be changed using the GUI as shown in Figure 2. Agents (vehicles) require reference points to follow the road network. For this purpose, an object path consisting of multiple interconnected nodes is created and placed on the road, and a C# script is attached to these objects. Buildings are created using the third-party software Blender. Other roadside infrastructure such as streetlamps, benches, and trees can be downloaded from the Unity Asset Store.

3.1.2. Traffic generation

After the road network and surrounding infrastructure have been created, agents can be initiated. LowPoly3D agents are employed as the computational complexity for rendering is lower than with other solutions. Object pooling is also used to improve resource utilization. This is done after the initial agents are instantiated, and eliminates the need to instantiate new agents and destroy old ones. During simulation, the current speed of every agent is displayed using Unity3D Canvas.

The following modules in the Unity3D tool NavMesh are used to create realistic agents. They are illustrated in Figure 3.

1. NavMesh surface is employed so agents can avoid obstacles. It is used to define walkable or drivable areas in the simulation environment.
2. NavMesh agents are employed for vehicle motion during simulation using properties such as agent size, steering, obstacle avoidance, and pathfinding. In addition, C# scripts are used with raycasting and object pooling to determine vehicle behavior in heterogeneous traffic. Raycast sensors such as left\right headlight, mid-front, and left\right door are used to make the agents move realistically.
3. NavMesh Obstacle is used with raycasting to improve agent motion in heterogeneous traffic.

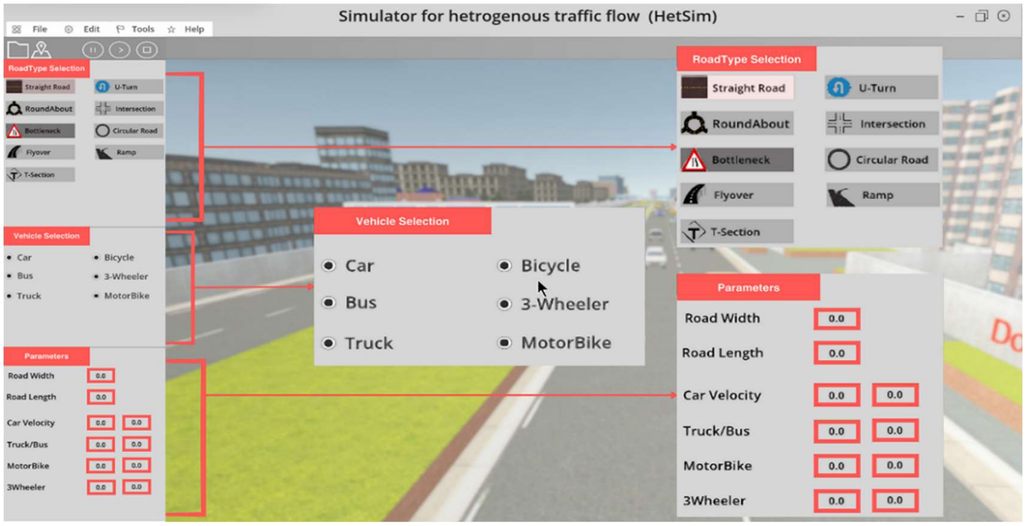

Figure 2. The HetroTraffSim graphical user interface (GUI).

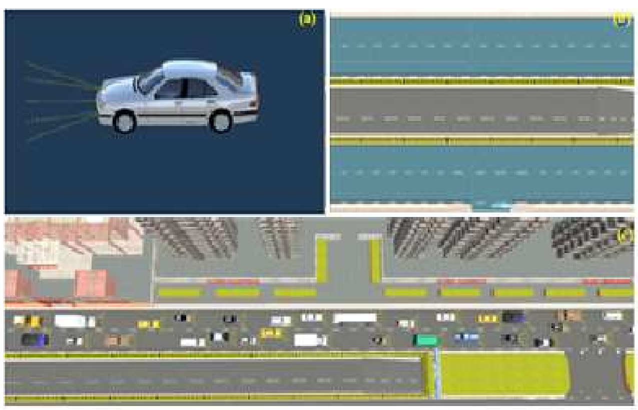

Figure 3. The (a) agent sensors, (b) NavMesh surface, and (c) simulation with agent sensors.

3.2. Traffic flow model

HetroTraffSim employs the two-equation Khan-Gulliver (KG) model for traffic flow [7]. With this model, vehicle alignment is based on the velocity difference between the forward and preceding vehicles and is quick for a small transition distance d_{tr}. The KG model can be expressed as

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho \upsilon)}{\partial x} = 0 \qquad (1)$$

$$(\rho\upsilon)_t + \left(\frac{(\rho\upsilon)^2}{\rho} + \left(\frac{\upsilon^2(\rho)-\upsilon^2}{2d_{tr}}\right)\rho\right)_x = \rho\left(\frac{\upsilon(\rho)-\upsilon}{\tau}\right) \qquad (2)$$

Where ρ is the traffic density, $\upsilon(\rho)$ is the equilibrium velocity distribution to which preceding vehicles align, and $\left(\frac{\upsilon^2(\rho)-\upsilon^2}{2d_{tr}}\right)\rho$ is the anticipation term. This model is based on driver presumption to forward changes so the spatial evolution of traffic is a function of the change in velocity and transition distance between vehicles.

The relaxation term is $\rho\frac{\upsilon(\rho)-\upsilon}{\tau}$ and indicates that traffic tends to the equilibrium velocity distribution. However, driver sensitivity is based on the relaxation time τ. When this time is small, driver sensitivity during alignment is large and stop-and-go behavior can occur. This is typical when lane discipline is not followed as drivers are more vigilant. With a large relaxation time, driver sensitivity is small and the flow is smooth. This is typical when there is lane discipline. The transition distance is

$$d_{tr} = \tau\upsilon_m + l_{s,} \qquad (3)$$

where $l_{s,}$ is the jam distance between vehicles at standstill. The KG model parameters are given in Table 1.

Table 1. Khan-Gulliver traffic flow model parameters.

Parameter	Description
ρ	Traffic density
$\upsilon(\rho)$	Equilibrium traffic velocity distribution
$\rho\upsilon$	Traffic flow
d_{tr}	Transition distance
$\rho\frac{\upsilon(\rho)-\upsilon}{\tau}$	Relaxation term
τ	Relaxation time
ρ_m	Maximum density

Several equilibrium velocity distributions have been proposed [15], but the Greenshields distribution [16] is the most popular. It is given by

$$v(\rho) = v_m \left(1 - \frac{\rho}{\rho_m}\right) \qquad (4)$$

Where ρ_m and ρ are the maximum and average traffic densities, respectively. The KG model is implemented in Unity3D using the ROE decomposition scheme [7]. This provides high resolution and can capture abrupt changes in flow [17, 18].

Figure 4. The section of University Road (33°59’51” N 71°29’29” E) considered for heterogeneous traffic flow simulation using HetroTraffSim.

4. Performance evaluation

In this section, HetroTraffSim is evaluated for a 360 m section of University Road in Peshawar, Pakistan (33°59’51” N 71°29’29” E). This road section is shown in Figure 4. It is a two-lane road with total width 8.85 m. It was implemented using the EasyRoads3D package in Unity3D. The road objects were grouped to form a two-lane straight road. A 360 m road section is considered and this is divided into 12 segments of length 30 m as shown in Figure 5. These segments were subdivided into sub-segments of length 10 m to observe traffic behavior at different times and distances.

To make the simulations more realistic and improve performance, LowPoly3D buildings were designed in Blender. The infrastructure created includes Khyber Teaching Hospital (KTH), Islamia College, and the University of Peshawar, as well as smaller objects such as trash cans, benches, street lights, and overhead pedestrian bridges. Some Modular City buildings from the Unity Asset Store were also used. The simulation environment is shown in Figure 6.

HetroTraffSim provides users with the capability to choose traffic parameters to obtain realistic simulation results. These parameters include road length\width, initial traffic density, time, and minimum\maximum velocity. At the start of the simulations, 6 instantiators were created to generate vehicles in three locations in each lane between 0.07 s and 1 s. Vehicles from the 9 types given in Table 2 were randomly chosen. In total, two hundred vehicles are instantiated randomly during the 5 s simulation time.

The dimensions of real vehicles were adjusted using Blender to ensure they fit on the road. The vehicle dimensions and maximum velocity used in HeterTraffSim are given in Table 2. This shows that the maximum velocity for any vehicle is 10 m/s. The vehicle speeds are based on the Greenshields distribution implemented using a C# script. The initial velocities are assigned randomly as vehicles are generated. The simulation time step is set to 1 s to ensure numerical stability based on the Courant, Friedrichs, and Lewy (CFL) conditions [19].

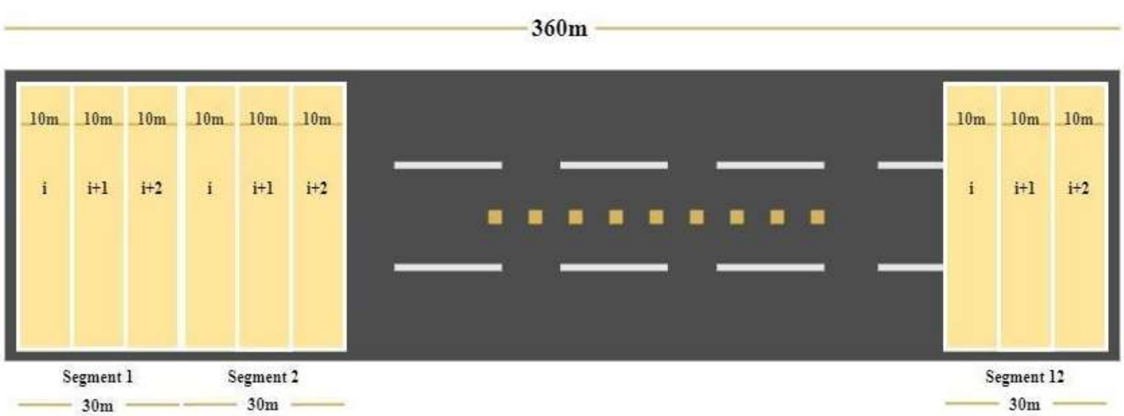

Figure 5. The road section divided into sub-segments.

Figure 6. HetroTraffSim simulation screenshots (a) front view and (b) top view.

Table 2. Vehicle type, dimensions, and maximum velocity.

Vehicle No.	Type	Dimensions (Width, Height, Length)	Maximum Velocity
1	Sedan	1.7 m, 1.4 m, 4.4 m	10 m/s
2	Hatchback	1.1 m, 1.5 m, 3.5 m	10 m/s
3	Sports Car	1.8 m, 1.3 m, 4.4 m	10 m/s
4	SUV	1.8 m, 1.5 m, 4.1 m	10 m/s
5	APV	1.8 m, 1.8 m, 4.3 m	10 m/s
6	Ambulance	2.0 m, 1.9 m, 5.4 m	9 m/s
7	Rickshaw	1.3 m, 1.7 m, 2.6 m	8 m/s
8	Pickup Truck	1.8 m, 1.8 m, 5.3 m	8 m/s
9	Bus	2.5 m, 2.9 m, 10.2 m	8 m/s

The simulations are performed at a standstill distance (headway at zero velocity) of 2 m and 10 m. The number of simulated vehicles on the road at a standstill distance of 2 m and 10 m is 180 and 36, respectively. The results for 1 s intervals are shown in Figure 7.

Figure 7: Simulation results at (a) 1 s, (b) 2 s, (c) 3 s, (d) 4 s, and (e) 5 s.

4.1. Traffic flow

The traffic flow on the 360 m straight road is given in Figure 8 and summarized in Table 3. At 1 s, the maximum flow is 2.95 veh/s at 150 m and 180 m, and the minimum flow is 0.99 veh/s at 30 m. At 2 s, the maximum flow is 2.95 veh/s at 210 m and 240 m. At 3 s, the maximum and minimum flow is 2.92 veh/s and 0.98 veh/s at 60 m and 300 m, respectively. At 4 s, the maximum and minimum flow is 2.96 veh/s and 1.93 veh/s at 150 m and 180 m, respectively. At 5 s, the maximum and minimum flow is 2.95 veh/s and 0.97 veh/s at 240 m and 330 m, respectively. Overall, the maximum flow is 2.96 veh/s at 4 s and 150 m, while the minimum flow is 0.97 veh/s at 330 m and 5 s.

4.2. Traffic velocity

The traffic velocity on the 360 m straight road is presented in Figure 9 and summarized in Table 4. At 1 s, the maximum and minimum velocity is 9.72 m/s and 6.21 m/s at 30 m and 270 m, respectively. At 2 s, the maximum velocity is 9.80 m/s at 30 m, while the minimum velocity is 5.20 m/s at 330 m. At 3 s, the maximum and minimum velocity is 8.91 m/s and 5.80 m/s at 210 m and 270 m, respectively. At 4 s, the maximum and minimum velocity is 9.30 m/s and 6.41 m/s at 210 m and 270 m, respectively. At 5 s, the maximum velocity is 9.12 m/s at 30 m and the minimum velocity is 6.80 m/s at 330 m as shown in Table 4. Overall, the maximum velocity is 9.80 m/s at 2 s while the minimum velocity is 5.20 m/s at 330 m and 2 s. This is much lower than the 6.10 m/s at 300 m.

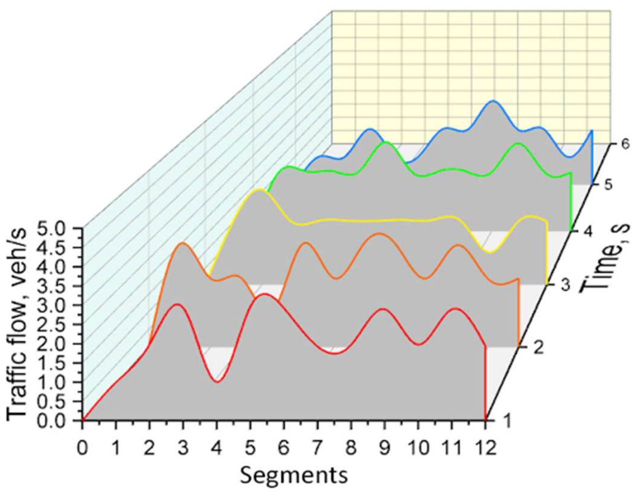

Figure 8. Traffic flow on the 360 m straight road.

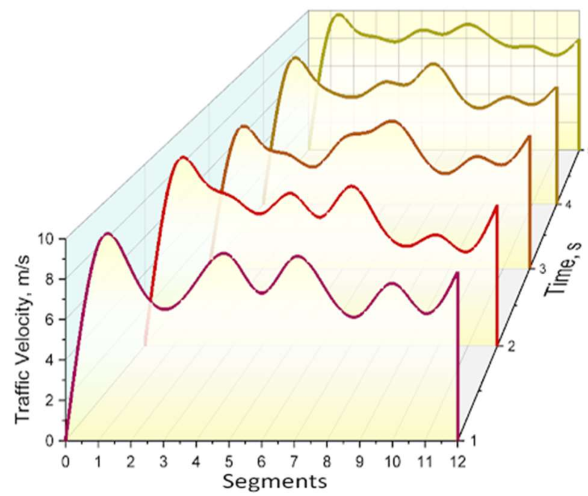

Figure 9. Traffic velocity on the 360 m straight road.

Table 3. Traffic flow on segments of the 360 m two-lane straight road over 5 s

Time	Traffic Flow (veh/s)											
	30 m	60 m	90 m	120 m	150 m	180 m	210 m	240 m	270 m	300 m	330 m	360 m
1 s	0.99	1.98	2.90	1.00	2.95	2.95	1.92	1.96	2.89	1.97	2.89	1.93
2 s	2.90	1.90	1.93	1.00	2.92	1.95	2.95	2.95	1.94	2.88	1.93	1.93
3 s	1.97	2.92	1.96	1.96	1.96	1.96	1.99	1.99	1.94	0.98	1.94	1.94
4 s	1.98	1.97	1.97	1.97	2.96	1.93	1.96	1.96	1.94	2.89	1.94	1.94
5 s	0.99	0.99	1.95	0.99	0.99	1.97	1.95	2.95	1.94	1.98	0.97	1.93

Table 4. Traffic velocity on the road segments at 1 s, 2 s, 3 s, 4 s, and 5 s.

Time	Velocity (m/s)											
	30 m	60 m	90 m	120 m	150 m	180 m	210 m	240 m	270 m	300 m	330 m	360 m
1 s	9.72	8.51	6.54	7.98	9.20	7.30	9.10	7.40	6.21	7.80	6.31	8.40
2 s	9.80	9.10	8.21	7.35	8.48	7.10	8.80	6.70	5.50	6.10	5.20	7.81
3 s	8.22	7.50	6.90	6.21	7.91	8.30	8.91	6.83	5.80	6.80	6.30	8.14
4 s	9.10	8.50	7.30	7.21	8.11	8.05	9.30	7.31	6.41	7.10	6.60	7.81
5 s	9.12	8.70	8.15	7.80	8.60	8.31	9.00	8.23	7.40	7.40	6.80	8.01

Table 5. Traffic density on the road segments at 1 s, 2 s, 3 s, 4 s, and 5 s.

Time	Density (veh/m)											
	30 m	60 m	90 m	120 m	150 m	180 m	210 m	240 m	270 m	300 m	330 m	360 m
1 s	0.294	0.196	0.196	0.097	0.293	0.196	0.293	0.293	0.196	0.294	0.196	0.196
2 s	0.196	0.294	0.097	0.196	0.196	0.196	0.195	0.195	0.196	0.097	0.196	0.196
3 s	0.098	0.098	0.196	0.097	0.097	0.195	0.196	0.293	0.196	0.195	0.098	0.196
4 s	0.196	0.293	0.196	0.293	0.293	0.098	0.196	0.097	0.098	0.196	0.196	0.196
5 s	0.097	0.195	0.293	0.097	0.293	0.293	0.196	0.195	0.294	0.195	0.294	0.196

4.3. Traffic density

The traffic density on the 360 m straight road is shown in Figure 10 and summarized in Table 5. At 1 s, the maximum density is 0.294 veh/m at 30 m and 300 m while the minimum density is 0.097 veh/m at 120 m. At 2 s, the maximum density is 0.294 veh/m and the minimum density is 0.097 veh/m at 90 m and 300 m. At 3 s, the maximum density is 0.293 veh/m at 240 m while the minimum density is 0.097 veh/m at 120 m and 150 m. At 4 s, the maximum density is 0.293 veh/m at 60 m, 120 m and 150 m, and the minimum density is 0.097 veh/m at 240 m. At 5 s, maximum density is 0.294 veh/m at 270 m and 330 m, and the minimum density is 0.097 veh/m at 30 m and 120 m. Overall, the maximum density is 0.294 veh/m at 1 s, 2 s, and 5 s and 30 m, 60 m, and 270 m and 330 m, respectively. The minimum density is 0.097 veh/m at 1 s, 2 s, 3 s, 4 s, and 5 s and 120 m, 90 m and 300 m, 120 m and 150 m, 240 m, and 30 m, 60 m and 120 m, respectively, as shown in Table 5.

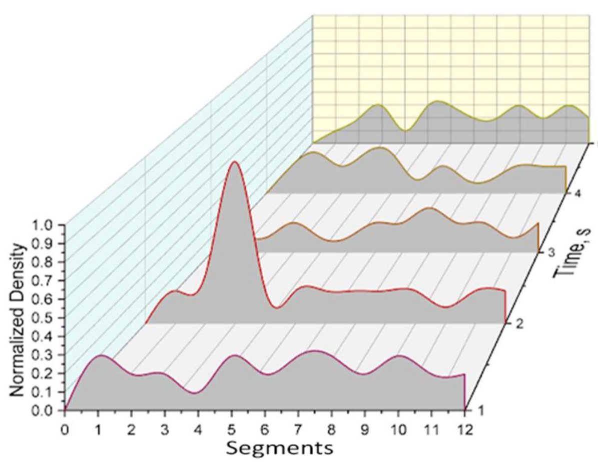

Figure 10. Normalized density on the 360 m straight road.

4.4. Fundamental traffic diagrams

The fundamental traffic diagrams illustrate the relationships between flow (veh/s), density (veh/m), and velocity (m/s). They can be used to predict the capability of a road system and the behavior with inflow regulation or speed limits [20]. In this section, fundamental diagrams are given for traffic velocity and density, and traffic flow and density, with 2 m and 10 m distance headways. Results are given for $\tau 1 = 1$ s, $\tau 2 = 2$ s, $\tau 3 = 3$ s, $\tau 4 = 4$ s, and $\tau 5 = 5$ s.

4.4.1. Velocity and density fundamental diagram

The fundamental diagram for velocity and density with a distance headway of 2 m is given in Figure 11. This shows the changes in velocity versus density over 5 s. At 1 s, the maximum velocity is 9.70 m/s at density 0.1 while the minimum velocity is 6.21 m/s at density 1 as shown in Table 6. At 2 s, the maximum and minimum velocity is 9.80 m/s and 5.21 m/s at density 0.1 and 1.0, respectively. At 4 s and 5 s, the maximum velocity is 9.11 m/s and 9.10 m/s, respectively, at density 0.1, and the corresponding minimum velocity is 3.60 m/s and 3.20 m/s at density 1.0.

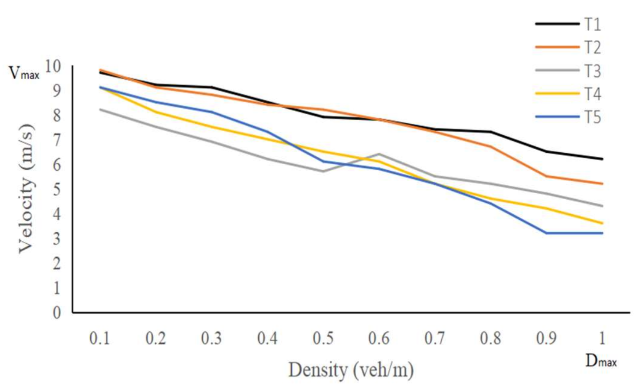

Figure 11. Velocity and density fundamental diagram with a 2 m headway at 1 s, 2 s, 3 s, 4 s, and 5 s.

Figure 12 gives the fundamental diagram for velocity and density with a 10 m distance headway. At 1s, the maximum velocity is 9.31 m/s at density 0.10, while the minimum velocity is 6.90 m/s at density 1.0 as shown in Table 7. At 2 s, the maximum and minimum velocity is 9.50 m/s and 5.71 m\s at density 0.1 and 1.0, respectively. At 3 s, the maximum and minimum velocity is 9.10 m/s and 5.20 m/s at density 0.10 and 0.80, respectively. At 4 s and 5 s, the maximum velocity is 9.14 m/s and 9.40 m/s, respectively, at density 0.10, while the corresponding minimum velocity is 4.41 m/s and 3.20 m/s at density 0.9 and 1.0.

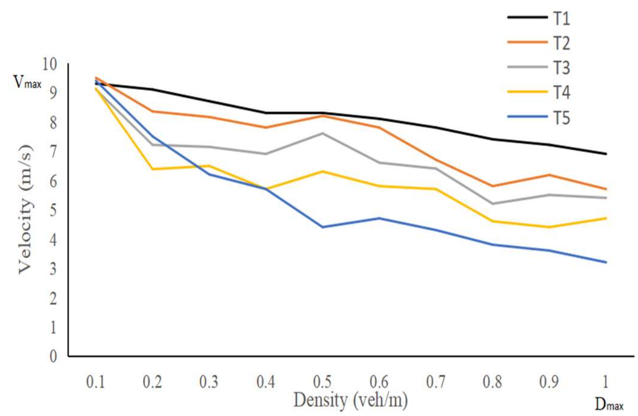

Figure 12. Velocity and density fundamental diagram with a 10 m headway at 1 s, 2 s, 3 s, 4 s, and 5 s.

Table 6. Velocity versus density with a 2 m distance headway at 1 s, 2 s, 3 s, 4 s, and 5 s.

	1 s	2 s	3 s	4 s	5 s	Density
Velocity (m/s)	9.70	9.80	8.21	9.11	9.10	0.1
	9.21	9.10	7.50	8.10	8.50	0.2
	9.10	8.80	6.91	7.50	8.11	0.3
	8.51	8.40	6.20	7.00	7.31	0.4
	7.90	8.21	5.71	6.51	6.10	0.5
	7.80	7.80	6.40	6.11	5.80	0.6
	7.40	7.30	5.50	5.20	5.20	0.7
	7.31	6.70	5.20	4.60	4.41	0.8
	6.50	5.51	4.81	4.20	3.20	0.9
	6.21	5.21	4.31	3.60	3.20	1.0

Table 7. Velocity versus density with a 10 m distance headway at 1 s, 2 s, 3 s, 4 s, and 5 s.

	1 s	2 s	3 s	4 s	5 s	Density
Velocity (m/s)	9.31	9.50	9.10	9.14	9.40	0.1
	9.11	8.36	7.21	6.38	7.50	0.2
	8.70	8.17	7.15	6.49	6.21	0.3
	8.31	7.80	6.90	5.70	5.71	0.4
	8.30	8.21	7.60	6.31	4.40	0.5
	8.11	7.80	6.61	5.80	4.70	0.6
	7.800	6.70	6.40	5.70	4.30	0.7
	7.40	5.81	5.20	4.61	3.80	0.8
	7.21	6.18	5.50	4.41	3.61	0.9
	6.90	5.71	5.40	4.70	3.20	1.0

Table 8. Flow versus density with a 2 m distance headway at 1 s, 2 s, 3 s, 4 s, and 5 s.

	1 s	2 s	3 s	4 s	5 s	Density
Flow (veh/s)	0.920	1.006	0.985	1.931	1.951	0.1
	1.513	1.426	1.921	2.206	2.433	0.2
	1.952	1.762	1.954	2.875	2.982	0.3
	2.537	2.733	2.961	2.904	2.611	0.4
	2.730	2.881	2.390	2.162	2.386	0.5
	2.104	2.178	1.994	1.968	1.926	0.6
	1.839	1.803	1.532	1.774	1.625	0.7
	1.632	1.355	1.000	1.585	1.211	0.8
	1.248	0.861	0.742	1.621	1.263	0.9
	0.921	0.416	0.468	1.686	0.980	1.0

4.4.2. Traffic flow and density fundamental diagram

The fundamental diagram for flow and density with a distance headway of 2 m is given in Figure 13. At 1 s, the maximum flow is 2.730 veh/s at density 0.60 while the minimum flow is 0.920 veh/s at density 0.10 as shown in Table 8. At 2 s, the maximum and minimum flow is 2.881 veh/s and 0.416 veh/s at density 0.60 and 1.0, respectively. At 3 s, the maximum and minimum flow is 2.390 veh/s and 0.468 veh/s at density 0.60 and 1.0, respectively. At 4 s and 5 s, the maximum flow is 2.904 veh/s and 2.982 veh/s at density 0.50 and 0.40, respectively, while the corresponding minimum flow is 1.585 veh/s and 0.980 veh/s at density 0.8 and 1.0.

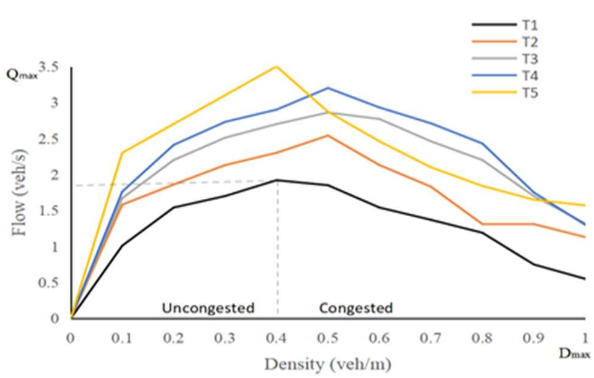

Figure 13. Flow and density fundamental diagram with a 2 m distance headway at 1 s, 2 s, 3 s, 4 s, and 5 s.

Figure 14 gives the fundamental diagram for flow and density with a 10 m distance headway. At 1 s, the maximum flow is 1.923 veh/s at density 0.5, while the minimum flow is 0.550 veh/s at density 1.0 as shown in Table 9. At 2 s, the maximum and minimum flow is 2.547 veh/s and 1.137 veh/s at density 0.6 and 1.0, respectively. At 3 s, the maximum and minimum flow is 2.861 veh/s and 1.328 veh/s at density 0.6 and 1.0, respectively. At 4 s and 5 s, the maximum flow is 3.277 veh/s and 3.571 veh/s at density 0.6 and 0.5, respectively, while the corresponding minimum flow is 1.300 veh/s and 1.571 veh/s at density 1.0.

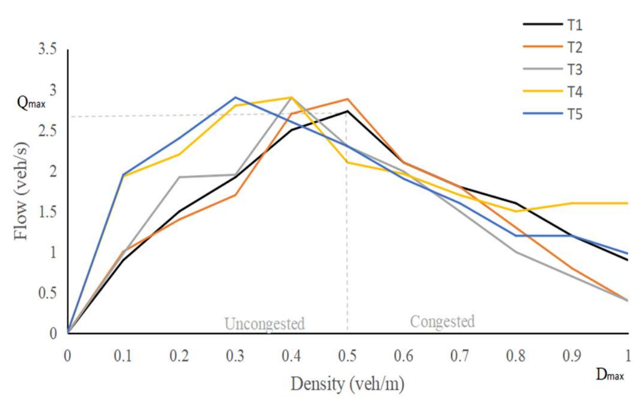

Figure 14. Flow and density fundamental diagram with a 10 m headway at 1 s, 2 s, 3 s, 4 s, and 5 s.

Table 9. Flow versus density with a distance headway of 10 m at 1 s, 2 s, 3 s, 4 s, and 5 s.

	1 s	2 s	3 s	4 s	5 s	Density
Flow (veh/s)	1.014	1.583	1.671	1.760	2.378	0.1
	1.543	1.860	2.258	2.411	2.755	0.2
	1.764	2.133	2.516	2.735	3.102	0.3
	1.923	2.362	2.736	2.961	3.571	0.4
	1.851	2.547	2.861	3.277	2.870	0.5
	1.542	2.138	2.771	2.932	2.463	0.6
	1.374	1.835	2.463	2.710	2.155	0.7
	1.192	1.313	2.217	2.438	1.843	0.8
	0.751	1.310	1.753	1.756	1.658	0.9
	0.550	1.137	1.328	1.300	1.571	1.0

The results presented in this section show that HetroTraffSim can easily and accurately simulate real traffic systems. Further, it can predict both homogeneous and heterogeneous traffic flow behavior. This is important because traffic flow in developed countries typically follows lane discipline but this is not the case in developing countries.

5. Conclusion

Existing TSS for heterogeneous traffic have drawbacks that limit their usefulness. This motivated the development of HetroTraffSim. It is based on Unity3D and employs a macroscopic traffic flow model. HetroTraffSim was evaluated using data from an actual road to demonstrate its capability to accurately predict traffic behavior. 200 vehicles (agents) were simulated for a period of 5 s. Fundamental diagrams were obtained to illustrate the relationships between traffic flow and density, and traffic flow and velocity. These results show there is an inverse relationship between velocity and density, and confirm the importance of incorporating density and velocity parameters in TSS to accurately predict heterogeneous traffic behavior. HetroTraffSim addresses the need for accurate heterogeneous traffic simulation. It will allow traffic engineers and planners to make informed decisions for traffic management, infrastructure design, and road network optimization. Further, HetroTraffSim can be used to predict autonomous vehicle behavior via raycasting.

Future work will incorporate additional traffic parameters in HetroTraffSim. This will improve the characterization of real traffic scenarios. Moreover, complex road infrastructure such as bottlenecks, U-turns, and roundabouts will be added.

Competing Interest Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data and Materials Accessibility

No additional data or materials were utilized for the research described in the article.

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