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Biomimicry of Foraging Ants for Traffic Flow Analysis and Design of Transportation System

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SUMMARY OF MASTER'S DISSERTATION

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Title

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Abstract

Traffic congestions in highways are everyday phenomena. Strong economies, population growth, higher employment rates and declining gas prices have resulted in more drivers on the road. This has led to increase in time wastage in traffic congestions. In London city, drivers have wasted 101 hours on average in 2015 and statistically the situations are similar around the world. Traffic congestions have critical impacts on modern-day city life. It leads to productivity loss, air pollution, increased stress level and wasteful consumption of energy. Therefore, it is vital to understand and solve the problem of traffic congestions.

On the other hand, Traffic like collective movements are observed at almost all levels of biological systems. Foraging ants, bird swarms, insect swarms, etc. are some of the examples of that. The important point is that all these phenomena have a commonality in terms of traffic system and also have the universality of jam formation therefore, by considering all entities for the various transporting process as "self-driven particles", we are allowed to treat various transportation phenomena universally as a same complex system. Although in past decade there have been multiple efforts to understand highway traffic using "self-driven particle" theory, most of these efforts are from the mathematic or physics perspective and does not explain the phenomena from the interdisciplinary point of view, therefore, the effort of system design based on the comparative study are lacking too.

In the first part of this thesis, analysis of the correlation between driving efficiency and traffic congestions on the highway is presented by an agent-based model of highway transportation system, where individual drivers are represented by agents undergoing single-lane unidirectional motion on a highway. Simulation results from above mention model show that with an increase in a number of vehicles on the highway, driving performance of drivers on same highway decreases, which leads to congestion formation on the highway.

The second part of this thesis compares traffic flow analysis of highway traffic with the traffic flow of foraging ant by comparing above mention model with the already established ant-trail model. This comparison reveals that flow in highway transportation can be improved by the introduction of a communication system in highway traffic. Based on this comparison this research proposed the concept of the communication-based intelligent transportation system. This intelligent transportation system will regulate traffic flow in highway transportation system.

Key Word(5 words)

Traffic Flow, Foraging Ants, Traffic Congestions, Intelligent Transportation System, Highway

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1 INTRODUCTION

The outline of this thesis is as follow, in chapter 1, we first provide the background information about traffic flow condition on the highway. In the same chapter under the subtopic “Mobility: one of the signs of life”, we explain the concept of “self-driven particles” and how ant transportation system is similar to the highway traffic. For the readers help we also explain NetLogo as agent-based modelling software which we have used as the simulator for different models. In chapter 2, we have explained the Asymmetric Simple Exclusion Process. In this chapter, we have defined most of the traffic-related basic terms such as jamming phase or critical density. In chapter 3 we explain the extension of ASEP model as a normally distributed-ASEP model. This model is used for the analysing effect of different drivers on the flow in the model. This lead to chapter 4: here we have explained the model of highway traffic to analyse traffic congestion. At the end of this chapter based on the simulation results of highway traffic, we compare highway traffic with foraging ant traffic. In chapter 5, based on the comparison from the previous chapter, we discuss conceptual system design of ant-trail based intelligent transportation system. The overall conclusion of this thesis is explained chapter 6. Chapter 7 is dedicated to acknowledgement and finally in chapter 8 all the references have been provided.

1.1 TRAFFIC FLOW ANALYSIS

1.1.1 Traffic congestion: problem definition

Traffic congestions in road network happen regularly. In modern-day life traffic congestions causes various kinds of losses, which includes loss of productivity, wasteful consumption of energy, serious environmental degradations, etc. Nowadays, we lose 38 hundred million hours every year in traffic jams, in other words, about 30 hours a year per capita [1]. Environmental burden of exhaust gas comes to double as the velocity of cars being reduced to a quarter. In terms of energy consumption, we consume two-and-a-half times more energy by reducing the velocity of cars to a quarter. Moreover, traffic congestions also have an adverse effect on mental health [12]. Therefore it is definitely important for economic and ecological effects to develop and use eco-friendly vehicles; however it is much more important to investigate the mechanism of jamming formation and ease the traffic congestions on the roads.

1.1.2 Traffic on highway:

Just like road networks in cities, Traffic on the highways has been overcrowded for many years. Reference [12] explains the condition of highway traffic through the investigatory observation study, based on data from the Japan Highway Public Corporation (Central Nippon Expressway) and the Metropolitan Expressway Public Corporation. Ref [12] explains the fundamental diagram1[1] for highway traffic.

Based on above mentioned fundamental diagram, characteristics of highway transportation can be summarised as follow,

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[1]The concept of the fundamental diagram is explained in section 2.1.1

- Critical density[2] (Cd) at around 20% of maximum capacity of the highway:

In the case of highway traffic change in phase from free flow phase to jamming phase[3] usually happen at 20% value of the maximum capacity of vehicles on the highway. This change in phase occurs because of the instability in equilibrium in a system, which leads to phantom jam on the highway. Phantom jams are traffic congestions that occur even without bottlenecks.

- Discrete single step drop in flow and average velocity at critical density:

In highway traffic system, change in flow and average velocity at critical density is not smooth or continuous. This change in flow has discrete one step drop nature. On the highway, at critical density flow in system discretely drops to about 2/3 of the maximum flow on the highway.

- The absence of zero flow scenario:

Data from highway observations have shown that even with 100% density, flow on highway never reduces to zero. Unless there is some serious situation such as road blockage or major accident which can completely block traffic on the highway, there always will be forward movement and these serious situations happen very rarely. Therefore zero flow scenarios are rare on the highways.

- Reverse-lambda shape of the fundamental diagram:

After the change in phase from free flow to jamming phase, highway data have shown that there is the continuous decrease in the flow of vehicles in the highway system; all these characteristics combinedly lead to reverse-lambda nature of fundamental diagram. Fig. 1 shows different characteristics of highway traffic that we discussed earlier.

[2] The concept of the fundamental diagram is explained in section 2.1.1

[3] The concept of free flow phase and jamming phase is explained in section 2.1.1

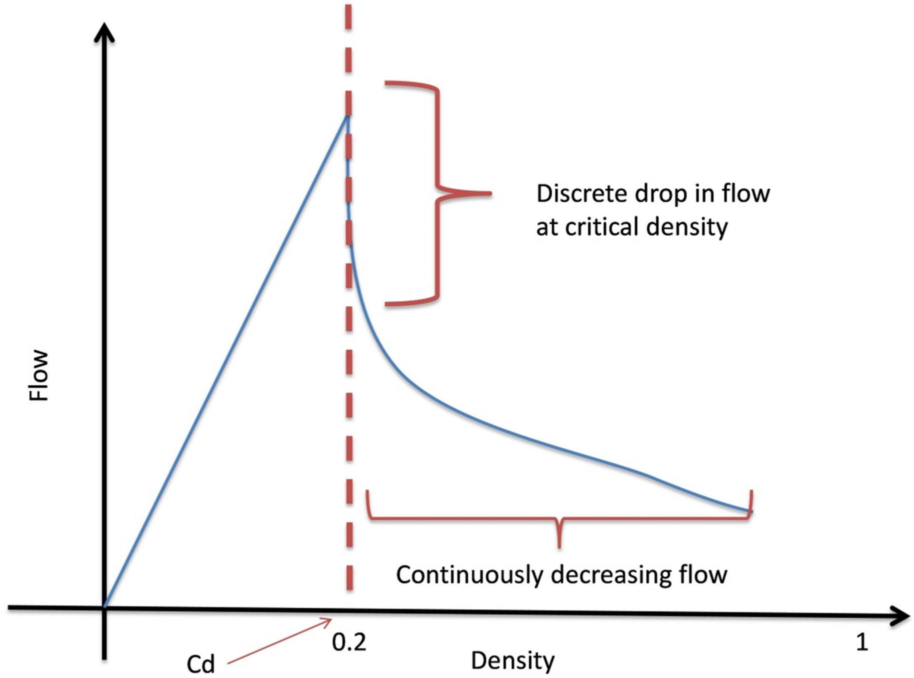


Figure 1 Schematic representation all the four characters of the highway traffic fundamental diagram.

1.2 MOBILITY: ONE OF THE SIGNS OF LIFE

The seven signs of life are moving, respiration, sensitivity, growth, reproduction, excretion and nutrition. As mobility is one of the seven signs of life therefore, in every aspect of life, there is motion. From crawling amoeba to big elephants travelling over continents, flow like motions exists everywhere around us. The important thing is that all of these phenomena have a commonality in terms of traffic congestion in transporting process and also have the universality of jam formation [5]. For humans, we see traffic congestions on the highway, or in the case of pedestrians in a corridor. Most of the times these congestions have a negative effect on the system that they are part of. But some time congestions also have a positive effect such as blood clotting and heat through electricity [12].

All these "moving entities" that we discussed above are called as self-driven particles (SDP). Self-driven particles have some or other kind of internal mechanism to generate force require for their movement [2]. These different phenomena of SDP are studied by using an interdisciplinary approach called as "jamology" [9]. In this study, vehicles, pedestrians, ants etc., are all regarded as self-driven particles, which are active particles and do not satisfy the Newton's law in general [2]. Dynamics of these particles are studied by using a rule-based model, e.g., cellular automata. These studies are intended, not only the scientific investigation of jamming phenomena, but also engineering applications of the results obtained so far, for making traffic flow smooth.

1.3 TRANSPORTATION IN ANT COLONY

Networks that control the flow of information, resources are an important part of the natural system. These networks determine the success of activity for these species which directly relates to the survival of species. Just as the productivity and management of modern cities depend on the transportation network, the effective management of transportation is also essential for insects' species [8].

Foraging ants are one of the examples of such network system. Many ant's species creates the chemical (pheromone) networks trail, not only to transport resource or information swiftly but also for coordinating a search of food and defense of the colony [6]. Ant colonies have more than half million worker ants; these ants are collectively responsible for food collection for the colony. These worker ants stage huge swarm raids in pursuit of food. Moreover, these massive raids are a time constraint, therefore, in order to be efficient, these ants have developed time efficient, communication-based transportation system [6]. This system depends on communication carried out by chemical signals to provide information about traffic condition on the trail.

Foraging ants communicate with each other by secreted chemical (generally called as pheromone). This chemical sticks to the ground and is not detected by human olfaction. Nevertheless, this chemical is used to create a track as well as to create information about the number of ants on trial and most efficient velocity on the same. Ants on trial can sniff this chemical. Based on the concentration of chemical ants can decode information about traffic on the trail [4].

1.3.1 Modelling of Ant-trail

In recent past, multiple observation experiments of ant transportation system have explained that contrary to most of the transportation system, the average velocity of the ant on the trail does not depend on the number of ants on the trail. In ref. [7], observations by D. Chowdhury et al have shown that on ant trail, the average velocity of ants is independent of density and remain almost constant with negligible variation; at the same time, flow in ant trail increases with increase in density. From results of above experiment, it is also clear that density of ants in trail never goes above 80% of its maximum value also deviation in the velocity of ants from its average value decreases with increase in density.

The Velocity vs. Density and Flux vs. Density graphs for above mention experiments are shown in ref. [7] we can verify above statements from those graphs.

- The conclusion of observation experiments:

Based on above results, we can conclude that ant in the trail, communicates with each other by using chemical signal. This communication system is used to provide information about the density and average velocity in the system. By using these information ants avoid density which could lead to traffic congestion also, due to the improvement in information with an increase in density, ants manage to reduce velocity deviation from average velocity for all ants.

1.3.1.1 Unidirectional Ant Traffic

Inspired by above mention research, many researchers have proposed cellular automata models to explain Single-lane unidirectional ant traffic [3, 8, 4, 11]. One of them called as “Unidirectional Ant-trail model” by K. Nishinari et al. (2008) is discussed below,

Particle hopping model is used to represent ant-trail traffic. Fig. 2 represents schematics of single-lane unidirectional hopping model that represents ant-trail. Rather than how the trail is created, this model explains how traffic moves on the previously created trail. For the purpose of simplicity, they have assumed only one directional traffic flow. As shown in Fig.2, to understand ant traffic we divided ant trail into L cells where each cell can occupy only one ant at a time. Whenever ant moves into next cell, it drops pheromone into its previous cell which, will be detected by the following ant. The concentration of this pheromone depends on the number of ants that has passed through that cell as well as it depends on the pheromone evaporation rate (f).

Therefore in this model specifications are as follow

- 'I' is the number of cell (1,2,3,………L)
- 'Si (t)' is parameter to represents presence or absence of ant in cell

  Si (t) = 1 {if ant is present in cell i at time t;

  Si (t) = 0 {if ant is not present in cell i at time t;

- 'Pi (t)' is parameter to represents presence or absence of pheromone in cell

  Pi (t) =1 {if pheromone is present in cell i at time t;

  Pi (t) =0 { if pheromone is absent in cell i at time t ;

- 'f'= pheromone evaporation rate

Movements in the ant-trail models are described with two step approach as follow

- Phase 1: the motion of ants: in the first step, ants verifies empty cell in from of it. after verification, ants moves into that cell with

  $$\text{Probability} = \begin{cases} Q & if \;\; pi(t) = 1 \\ q & if \;\; pi(t) = 0 \end{cases}$$

  Where, Q > q

Before moving in, ants drop pheromone in the previous cell to increase the concentration of pheromone in that cell.

- Phase 2: pheromone evaporation: In this step pheromones in all the cell evaporated with evaporation rate (f)

- Therefore value of pi(t+1) is given by the following expression

  - $$pi(t+1) = \begin{cases} 0 & with\ probability\ f \\ 1 & wi \quad probability\ 1-f \end{cases}$$

for f close to 0 free flow phase is up to 70% of maximum capacity of the model also, the average velocity of ants in model remain constant with a negligible drop in free flow phase. Based on this information we can conclude that, in free flow phase of the ant-trail model with an increase in density, flow in the model increases whereas, average velocity remains constant. This expansion of free flow phase in the fundamental diagram of the ant-trail model is the result of better information because of the low value of pheromone evaporation rate (f) and increase in density. Therefore we can say that in ant-trail due to the improvement of information there is larger free flow phase, hence, in ant trail efficiency of transportation increases due to better communication of information and this information improves with an increase in density.

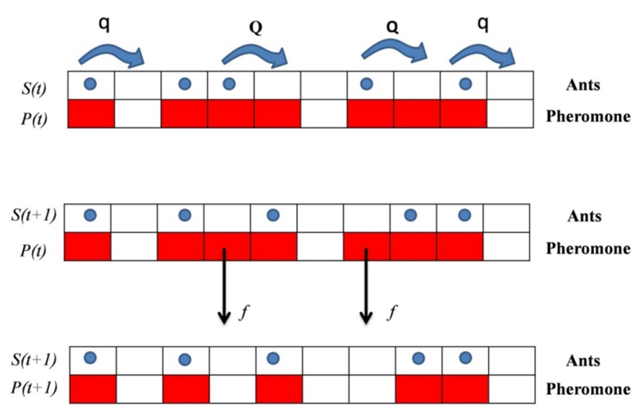


Figure 2: Schematics of hopping model is parallel updating for five discrete time steps. In this model one-dimensional track is divided into 10 cells and particles (represented by red dots) are moving from left to right, with hopping probability is denoted by p(movement of particles in indicated by black curved arrow). In the model, the inflow and outflow rates are denoted by α, β respectively (represented by blue arrows.The hopping model for unidirectional flow is represented as in fig. 2. Fig. 2 shows hopping model where particles are moving from left to right in the discrete time step. In this model, the track is divided into 10 cells. It begins at i=1 and ends at i=10. At the point i=1 particles are introduced in a model with inflow 'α' and at the point, i=10 particles are taken out of the model with outflow 'β'

1.4 NetLogo: Agent-based Modelling Language

As discussed earlier, due to the presence of the non-Newtonian forces, self-driven particles models cannot be studied using conventional mechanics. At the same time most often, models of self-driven particles have emergent phenomena. Therefore in self-driven particle models simple entities called as particles, operate in an environment which collectively leads to more complex system behaviour. In order to understand these emergent phenomena, we need to capture the individual behaviour of particles as well as the collective behaviour of the system in the model. In order to do that self-driven particle, models are studied using agent-based modelling, where different particles are represented by individual agents.

In our research, we used NetLogo software [13] to simulate an agent-based model of self-driven particles. NetLogo is programmable modelling language which can be used to simulate agent-base modelling and its environment. It was produced by Uri Wilensky and it is continuously developed by the centre for connected learning and computer-based modelling.

Based on requirement of our study, Features of NetLogo are divided into three types as given bellow,

Patches

Agents

Interface

1.4.1 Patches:

In NetLogo, patches are used to create an environment in the model. Mostly elements that cannot move are represented by patches in the model for example road, grassland, buildings etc. it is also used to represent boundaries of model or size of the model. As shown in the Fig. 3, NetLogo model is comprised of multiple patches represented by points in the Cartesian coordinate system. All patches in given model are same and their size can be alter using settings. In NetLogo world, patches at the end of the world can be connected to the beginning of world by using “World wraps horizontally”. Same goes for vertical patches where topmost patches can be connected to last one by using “world wraps horizontally”. Screenshot of patches sitting in Netlogo is as shown in Fig.3.

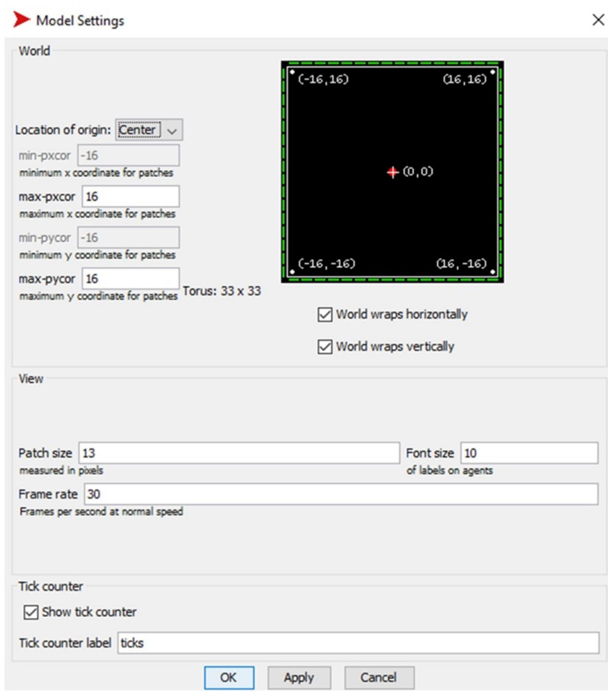


Figure 3: The Screenshot of model setting about patches in the NetLogo. This screenshot represents different patches settings that we can control in NetLogo. It also illustrates Cartesian coordinate representation of patches in NetLogo [13].

1.4.2 Agents

In the NetLogo, agents represent movable elements of the model, for example, in Netlogo, we can represent cars, ants, humans etc. by using agents. NetLogo gives us ability to program these agents separately or as a group. Depending on their programs, agents in Netlogo interact with other elements of the model. Agents in Netlogo interacts with other agents or patches, they can change properties of those agents and patches depending on the model program. The shape of NetLogo agents can be selected from available predetermined shapes, such as cars, wolf, sheep, etc. As per the need of a programmer, depending on shape, colour, size, etc. agents can be divided into multiple sets. The following Fig. 4 shows the screenshots of some of the agents' types in NetLogo,

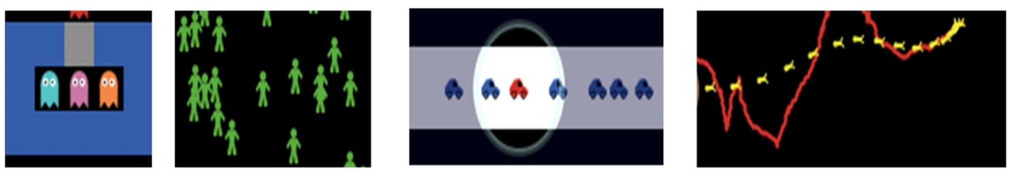


Figure 4: Screenshot: an example of different agents in Netlogo model. Starting from the leftmost side, Sequentially a) Packman from the Packman game, b) humans, c) cars, d) ants are respectively presented in figure [13].

1.4.3 Interface:

NetLogo has multiple types of interfaces. These interfaces are useful while controlling variables in the model, also these interfaces are used for monitoring inputs/outputs of simulation. Netlogo has a large number of interfaces but in order to help reader here, we will only discuss those interfaces that have been used in our model. Fig. 5 is a screenshot of all the interfaces that we used in our model. Fig. 6 is screenshot with names of all the interfaces that are available in Netlogo.

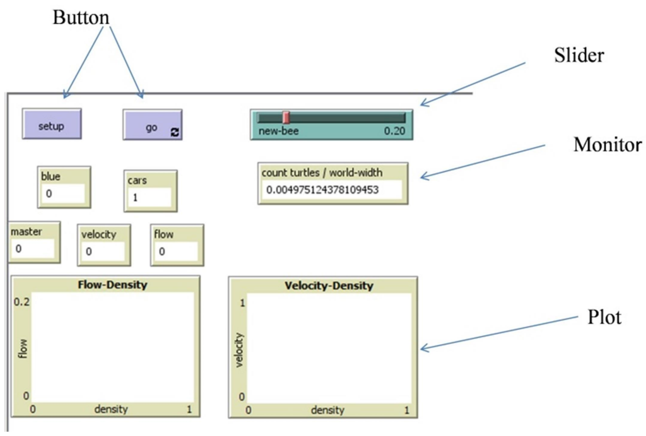


Figure 5: The screenshot illustrates different interfaces that we used in our model of highway traffic [13].

Figure 6: The screenshot of names and symbol of all the available interfaces in the NetLogo [13].

1.4.3.1 Button:

In Netlogo button is use to carry out a certain process, which is described in the program for the corresponding button. Netlogo has two types of buttons

Forever button: when you press forever button it start the certain process. And the process is repeated until you press the button again or certain code in the program make it stop. in our model "go" button is forever button which starts the simulation and continues it until in program certain code stops it or we click it again.

Non-forever button: when you press the non-forever button, model carries out certain process only one time and then it stops it. In the case of a non-forever button, you don’t have to terminate the process by doing any action. In our model, “setup” is a non-forever button.

1.4.3.2 Slider:

In NetLogo slider is use to change the value of variables in the model, a value such as a number of cars, the speed of car etc. can be changed by moving the slider to different values.in our model, “new-bee” is slider name which controls the percentage of amateur drivers in the model.

1.4.3.3 Monitor:

Monitors are used to display numerical inputs/outputs of simulations. In our model, we have used multiple monitors to record different parameters such as the number of different cars or density of cars in the model.

1.4.3.4 Plot:

In NetLogo plot can be used to create graphs from simulation results. It gives us a clear understanding of progressing of a certain phenomenon in the model. it also helps us to understand the interdependence between different variables in the model. in our model, we used plot interface to plot a fundamental diagram as well as Avg. velocity vs. density graph.

2 ASYMMETRIC SIMPLE EXCLUSION PROCESS: SIMPLE MODEL OF SINGLE-LANE TRAFFIC

2.1 Asymmetric Simple Exclusion Process

The asymmetric simple exclusion process (ASEP) is a simple and solvable a particle-hopping model [5]. In particle-hopping models, particles can hop (with a certain probability ‘p’) from one lattice site to neighbouring one in any direction. On the other hand, in ASEP particles can only hop (with a certain probability ‘p’) from one lattice site to neighboring in a one- dimensional world. Another important rule that is followed in ASEP is that movement is allowed only if the target site is not occupied by another particle. In ASEP “Simple Exclusion” represents that each site would only be occupied by one or no particle at all the time. Generally, particles in ASEP have preferred direction; therefore, flow in ASEP is asymmetric and lack equilibrium. ASEP with unidirectional traffic is called Totally Asymmetric Simple Exclusion Process.

In order to define the model in a complete way, it is important to explain the way in which the rules described above is to be applied to the particles. The most common update types are random-sequential updating and parallel updating. For the random-sequential updating, cells are chosen in random order and then updated. On the other hand, updating in the parallel case is done in a synchronous way; here all the sites are updated at same time.

Most often ASEP is studied in one-dimensional model, where particles move along a linear chain of L cells. This is similar to many natural and human phenomenon, e.g. highway traffic, ant trail. In these situations, the motion is allowed in only one direction (e.g. positive x direction on Cartesian coordinate axis), the corresponding model is called as Totally Asymmetric Simple Exclusion Process (TASEP). The probability of particle moving from cell i to site i +1 will be indicated by p; for example, in the simplest case, when all the sites are treated on equal footing, p will be independent of the particle location.

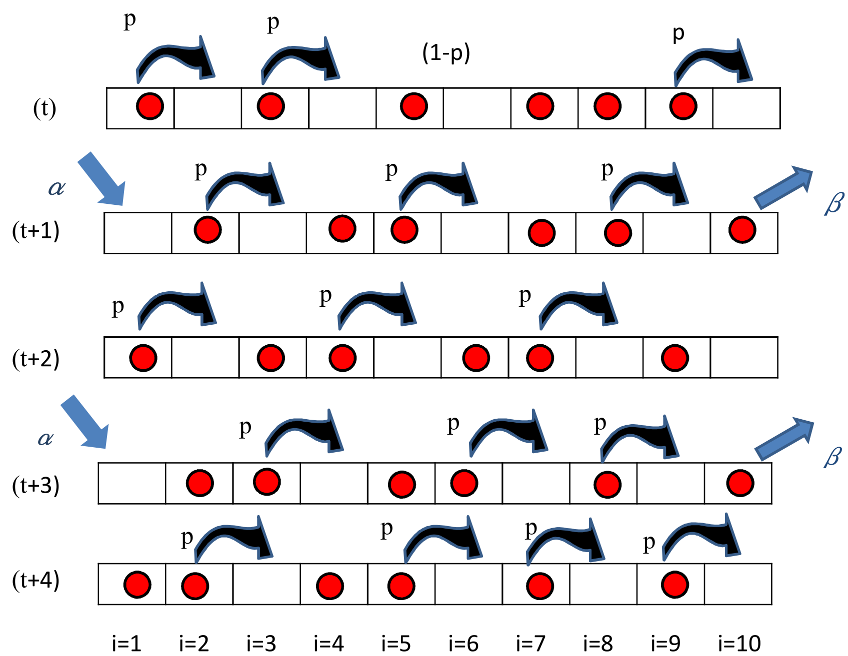


Figure 7: Schematics of ASEP model is parallel updating for five discrete time steps. In this model one-dimensional track is divided into 10 cells and particles (represented by red dots) are moving from left to right, with hopping probability is denoted by p(movement of particles in indicated by black curved arrow). In the model, the inflow and outflow rates are denoted by α, β respectively (represented by blue arrows).

The ASEP model for unidirectional flow is represented as in Fig. 7. Fig shows ASEP model where particles are moving from left to right in the discrete time step. In this ASEP track is divided into 10 cells. It begins at i=1 and ends at i=10. At the point i=1 particles are introduced in a model with inflow ‘α’ and at the point, i=10 particles are taken out of the model with outflow ‘β’.

2.1.1 Transportation system Trade-off: system views vs. individual views.

2.1.1.1 The fundamental diagram

For ASEP model the fundamental diagram can be derived for both cases (random-sequential dynamics and parallel dynamics). In both cases, the fundamental diagram is as shown in Fig. 8. The fundamental diagram is flow vs. density graph here flow is a product of density and average velocity in the system. For systemic point of view, the fundamental diagram is the most important and efficient way to represent and analyse flow characteristics of a traffic model. This behaviour of the fundamental diagram is common in most of the traffic phenomenon [4].

Based on this fundamental diagram traffic flow of ASEP system has following three characteristics as follow,

- Characteristic I: free flow phase: in this phase of fundamental diagram, flow of particles in model increases with increase in density
- Characteristic II: jamming phase: in this phase of fundamental diagram, flow of particles in model decreases with increase in density
- Characteristic III: Critical density (Cd): The density at which change in phase occur is called as the critical density of model. In this model, Cd was at 0.5,

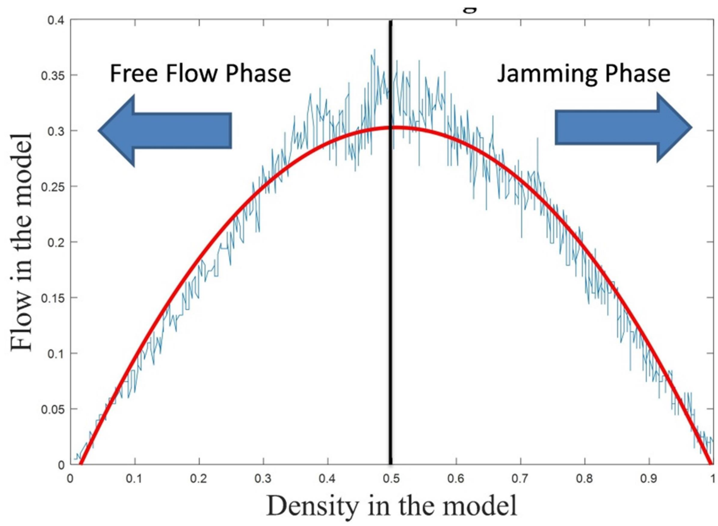


Figure 8: The fundamental diagram of ASEP model: the flow of particles in the model is plotted against the density of particles in the same model. Blue line represents flow in the model at different discrete times whereas red line represents the average value of flow in the ASEP model. This diagram represents three main characteristics of the transportation system. 1) Free flow phase: corresponds to increasing flow with density, 2) Jamming phase: corresponds to decrease in flow with density, (3) Critical density (Cd): density at which phase transition happen. For this fundamental diagram, it was at 0.5.

2.1.1.2 Average velocity vs. density graph

For the same ASEP model, it is interesting to observe average Velocity vs. Density graph. Average velocity vs. density graph represents dynamics of traffic flow from the individualistic point of view. Therefore it is interesting to compare fundamental diagram and average velocity vs. density graph in order to understand tradeoff between system perspective and individual perspective. From the driver's individual point of view, we can assume that jamming phase will be the state where velocity decreases with density. Therefore similar to fundamental diagram average velocity vs. density graph can be divided into two phases. Two distinct phases of this graph are as shown in Fig. 9.

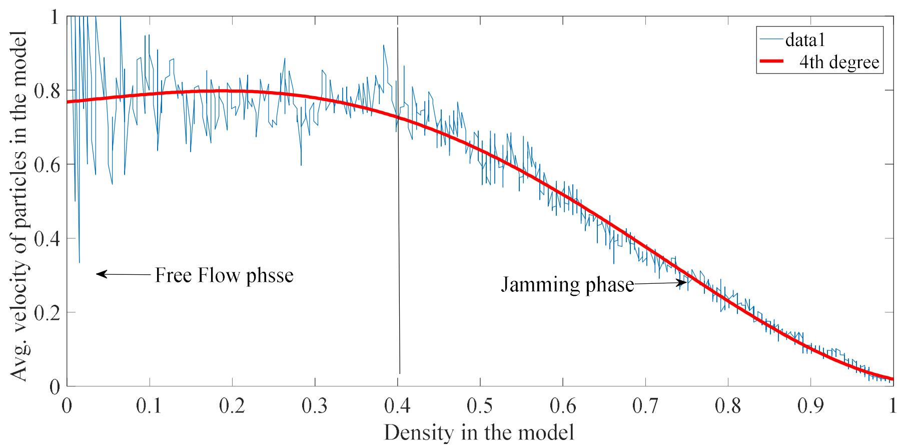
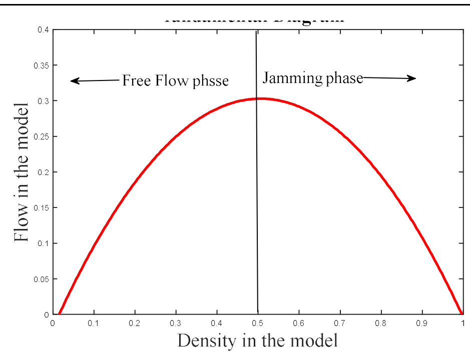
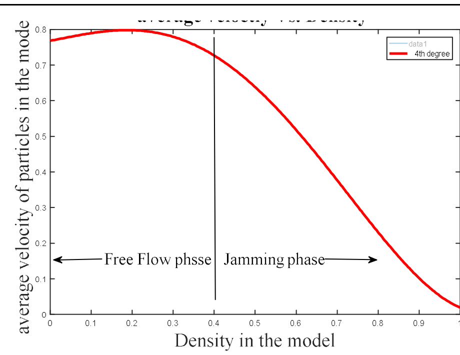


Figure 9: The average velocity vs. density diagram of ASEP model: average velocity of particles in the model is plotted against the density of particles in the model. In this diagram, the blue line represents the average velocity of individual particles in model whereas red line represents the average velocity of all the particles in the same model. This diagram represents 3 main characteristics of the transportation system. 1) Free flow phase: corresponds to almost constant velocity with density, 2) Jamming phase: corresponds to decrease in average velocity with density, (3) Critical density (Cd): density at which phase transition happen. For this diagram, it was at 0.4.

2.1.1.3 Comparison between system views vs. individual views.

At this point, it is important that we should differentiate between system viewpoint vs individual viewpoint for ASEP. It is also important to understand the correlation between them following table 1 is the comparison between system viewpoint and individual viewpoint for ASEP model that we discussed earlier.

Table 1: Comparison between system views vs. individual views

System viewpoint in ASEP	Individual viewpoint in ASEP
For ASEP system viewpoint is represented by fundamental diagram i.e., flow vs. density graph here flow is the product of density and average velocity.	For ASEP individual viewpoint is represented by average velocity vs. density graph.
As flow is the product of density and average velocity, flow in ASEP depends on average velocity; therefore, a system performance depends on individual performance.	Individual performance does not directly depend on system performance.
 **Figure 10: The fundamental diagram of ASEP**	 **Figure 11: The Avg. velocity vs. density graph for ASEP**
System viewpoint in ASEP	Individual viewpoint in ASEP

Jamming phase: jamming phase for system viewpoint corresponds to a monotonic decrease in flow with an increase in density.	Jamming phase: jamming phase with individual viewpoint corresponds to a monotonic decrease in average velocity with an increase in density.
Critical density: critical density for system viewpoint is at 50% of maximum density.	Critical density: critical density with an individual viewpoint is at 40% of maximum density.

2.1.2 Inflow, Outflow and Density Co-Relation in ASEP

In any transportation system inflow and outflow of moving particles in the system plays a crucial role in the density of particles in the system. If the mechanism of flow inside system remains constant, the relation between inflow, outflow and density can be explained as shown in the Fig. 12. The same Fig. represents the relationship between inflow (α) outflow (β) and the flow of particles in the model

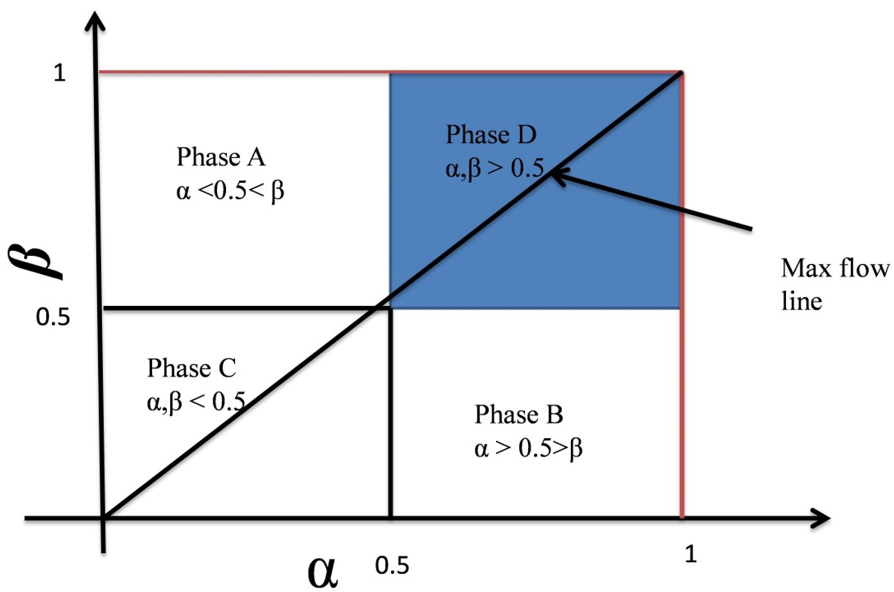


Figure 12: Schematic representation of the correlation between inflow (α), outflow (β), and flow in the model. This relation can be divided into 4 phases as shown in the figure. Phase A: low-density phase; Phase B: high-density Phase C and D: flow in the system does not depend on the inflow or the outflow.

As shown in figure relationship between inflow (α) outflow (β) and density in model can be divided into four phases those four phases are as follow,

Phase A (α<0.5<β): in phase 'A' the outflow in the model is higher than the inflow in the same model, therefore, the number of particles coming in the system is lower than a number of particles leaving the same system hence the density of particles in the system in this phase is normally lower. This phase is called as a low-density phase.

Phase B (α>0.5>β): in phase 'B' the outflow in the model is lower than the inflow in the same model, therefore, a number of particles coming in the system are higher than a number of particles leaving the same system hence the density of particles in the system in this phase is normally lower. This phase is called as a low-density phase.

Phase C (α, β< 0.5): in phase 'C' the outflow in the model and inflow in the same model is less than 0.5. In this phase of the model value of inflow and outflow is small enough; therefore, they do not produce any significant collective effect on density and flow.

Phase D (α, β> 0.5): in phase 'D' the outflow in model and inflow in the same model is higher than 0.5. In this case normally, flow in the system is high and does not depend on inflow or outflow.

2.1.3 Modelling randomness in ASEP model

There are at least three different ways in which we can model randomness in the hopping rates in the context of the ASEP-type models.

First, the randomness can be realised with the track on which the particles move; typical examples are the bottlenecks creation.

The second type of randomness is associated with the hopping particle, rather than with the track. In this way, we model elements in such way that there hopping probability changes differently for different particles. An example of this method is different types of particles and agents which hop with different probabilities.

In contrast to the two types of randomness ((a) and (b)) considered above, the randomness in the hopping probabilities of the particle in some situations arises from the coupling of their dynamics with that of another non-conserved dynamical variable. For example, the hopping probability of particles may depend on the presence or absence of a specific type of signal molecule in front of it.

3 NORMALLY DISTRIBUTED-ASEP MODEL: STUDY OF DRIVERS' TYPES AND THEIR EFFECTS ON THE FLOW OF SINGLE-LANE TRAFFIC MODEL

3.1 Normally Distributed-ASEP Model

The ASEP models that we described in section 2.1 were assumed to be with uniform agent type i.e., all the agents had similar skills, similar reaction, and similar approach to situations but in real world above mention uniformity is not true, in real-world every human is a different from each other and has their own way of dealing with things. Thus in order to simulate real-world diversity in ASEP modelling, we introduce diversity in the types of agents in the model.

Although every human has a different way of thinking, most of the time we also have similarities in our way of thinking. These similarities are driven by human factors, such as age, experience, environment and etc. Based on these human factor driving skills of drivers can be divided into two categories i.e., "Average Drivers" and "Anomalous Drivers"; furthermore, anomalous drivers can be further divided into "Amateur Drivers" and "Expert Drivers" this is explained as follow. For the purpose of simplicity here after we consider that there are three types of basic drivers as follow and in Fig. 13,

1) Expert drivers

2) Average drivers

3) Amateur drivers

These categories are mutually exclusive and therefore no one drivers can be in two categories at the same time. In human factor studies, these categories can have a hard definition but for the purpose of our study we have defined these categories ambiguously. For our study, we have assumed relationship between different categories as to be in Fig. 14

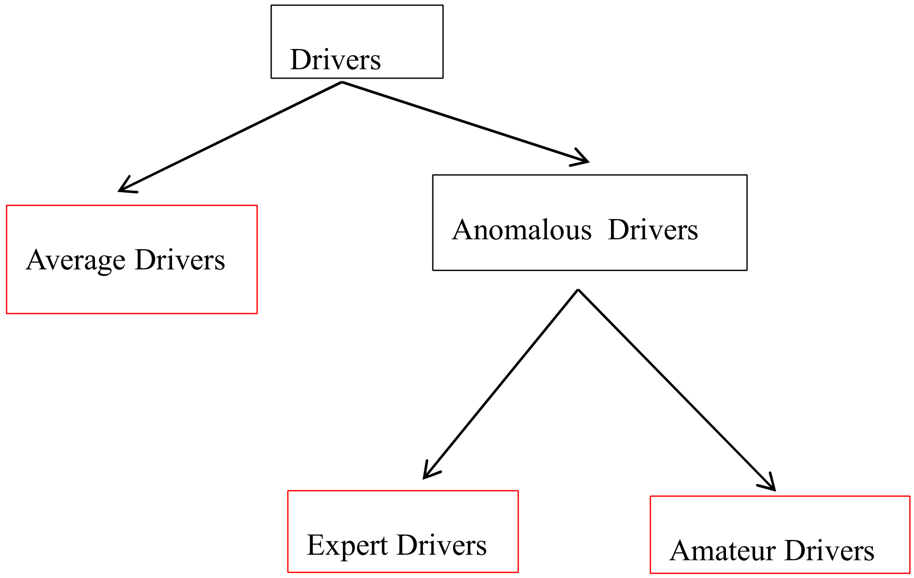


Figure 13: Categorisation of the drives based on driving skills of drivers. This categorisation divides drivers into three mutually exclusive categories i.e., "Expert drivers" , "Average drivers", "Amateur drivers".

Figure 14: schematic representation of driving skill comparison of the different type of drivers that have been explained in Fig. 13. Mathematical sign of ' less than' is used to indicated the difference between different drivers types.

For simple understanding driving skills were defined in a comparative way as follow,

Driving skills of "Expert drivers" were considered as highest and near to perfection therefore driving skills of "Expert drivers" are assumed to be immune to the effects of human factors and surrounding environment, whereas driving skills of "Average drivers" were considered as in between "Amateur drivers" and "Expert drivers". On the other hand driving skills of "Amateur drivers" were considered as lowest and therefore they are influenced by human factors and surrounding environment. Normally in most of the social systems distribution of subjects is assumed to be a normal distribution. Therefore in our model also we assumed that distribution of different types of drivers is a normal distribution. Normal distribution is represented by a bell-shaped curve as shown in Fig. 15, where most of the population is assumed to be concentrated near average value. So in our system majority of drivers are assumed to be "Average drivers" whereas small fraction of total drivers in model was assumed to be "Expert drivers" or "Amateur drivers"

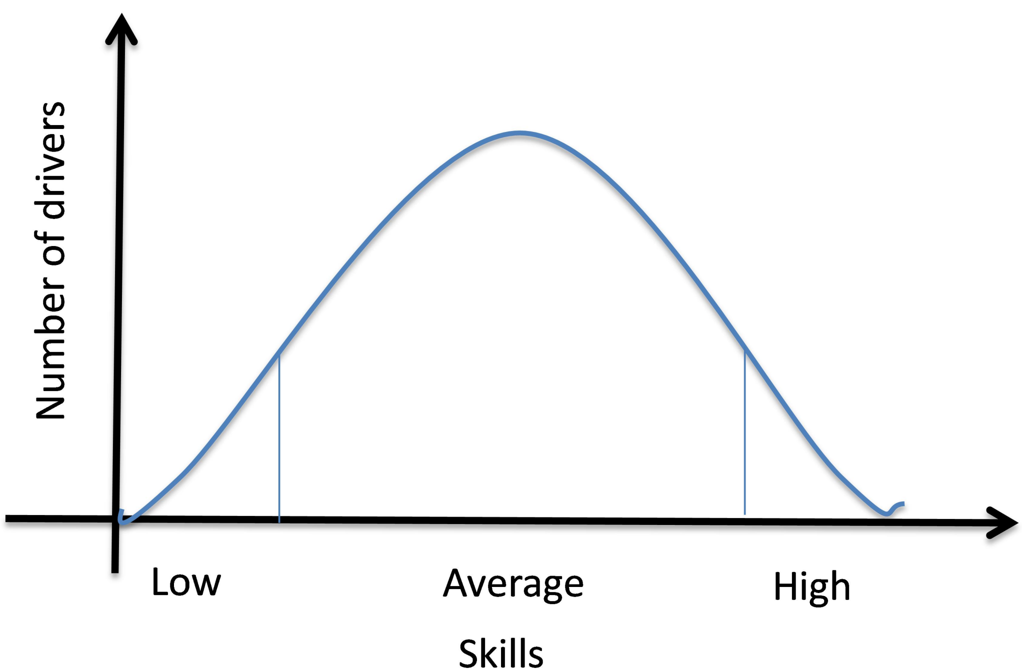


Figure 15: Schematic representation of normal distribution: bell-shaped graph of a number of drivers vs. skill.

Based on normal distribution discussed earlier, agents representing drivers in the model were divided into three categories randomly. Those three categories are as follow,

- Type I: drivers with high driving efficiency (expert drivers) consist of 10 – 20 % of all drivers in the model.

- Type II: drivers with average driving efficiency (average drivers) consist of 60-80 % of all drivers in the model.

- Type II: drivers with low driving efficiency (amateur drivers) consist of 10-20 % of all drivers in the model.

In our model, we have differentiated driving efficiency from driving performance. Driving efficiency is considered as a measure of driving skill, therefore, it does not depend on the number of opportunities that drivers get to move forward in the model. In our model driving efficiency is represented by hopping probability of drivers; whereas driving performance is considered as the effectiveness of driving activity in the model and hence it depends on number of opportunities that drivers get to move forward in the same model, it can be correlated to the average distance travel by the driver in given time (average velocity). Therefore in our model, driving performance of driver depends on driving efficiency of the same but the vice versa scenario is not always true. This concept can be explained with the following example:

"Imagine an expert driver on a highway is moving in a certain direction. Now in the case of certain unexpected events, such as traffic accident, or security check; that driver has to reduce his/her velocity, he/she might also have to stop for a certain period of time. Naturally, this reduction in velocity will lead to a delay in travel time for the driver. But that does not mean that there was any loss in driving skill of the driver. Even with same driving skills because of reduction in opportunity performance of driver was reduced."

In our study above mention performance of the driver is considered as driving performance while as driving skills of drivers were considered as driving efficiency. Relationship between driving efficiency and driving skill mathematically can be represented by equation

$$driving\ perfomance\ function\ (driving\ efficiency, \dots\dots)$$

Therefore in the simple words, this relation can be stated as follow

"Driving performance is a function of driving efficiency."

Based on the discussion in this chapter, following specification of agents for ASEP model was decided. We call this model as "Normally Distributed-ASEP model". Table 2 represents specifications of different types of agents in the model.

Table 2: Specifications of Drivers in Normally Distributed-ASEP model

Driver type (agent Type)	Composition specification	Hopping probability specification (HP)
Expert drivers	Consist of 10% to 20% of a total number of drivers in the model.	$0.7 \leq HP < 0.9$
Average drivers	Consist of 60% to 80 % of total number of drivers in model	$0.5 \leq HP < 0.7$
Amateur drivers	Consist of 10% to 20% total number of drivers in model.	$0.1 \leq HP < 0.5$

Based on above composition three different sets of simulations were carried out to understand the effect of the different composition of drivers on the performance of the normally distributed-ASEP model. Following are three different relations that were tested in simulations

- Effect of expert drivers on system performance
- Effect of average drivers on system performance
- Effect of amateur drivers on system performance

All these three simulations are discussed in detail in next section.

3.1.1 Effects of different types of drivers on the flow in the normally distributed-ASEP model

3.1.1.1 Relationship between Expert drivers and the flow in the model

- Model

The aim of this set of simulation is to understand the correlation between expert drivers and system performance. In order to do that in our simulation, we kept other variables constant,

Table 3: Specifications of simulation

Simulation set I (hopping probability variation)		
Drivers type	Composition	Hopping probability 1^{st}, 2^{nd} simulation
Expert Drivers	10 %	0.9, 0.8
Average drivers	80 %	0.7
Amateur drivers	10%	0.4
Simulation set II (composition variation variation)		
Drivers type	Composition 3^{rd} , 4^{th} simulation	Hopping probability
Expert Drivers	10 %, 20 %	0.9,
Average drivers	80 %	0.7
Amateur drivers	10%, 20%	0.4

therefore in this set of simulations hopping probability and composition of amateur and average drivers was kept constant whereas specifications of expert drivers were varied in given limit. Simulations were carried out separately for hopping probability variation and composition variation Specifications for different simulations are given in table 3.

- Results of simulation:

As we discussed earlier system performance is measured using the fundamental diagram, therefore, we compare four fundamental diagrams of above-discussed simulation of the normally distributed-ASEP model. We also compared average velocity vs. density graph to see changes in individual performance. Simulation results were as shown in the Fig. 16 and Fig. 17

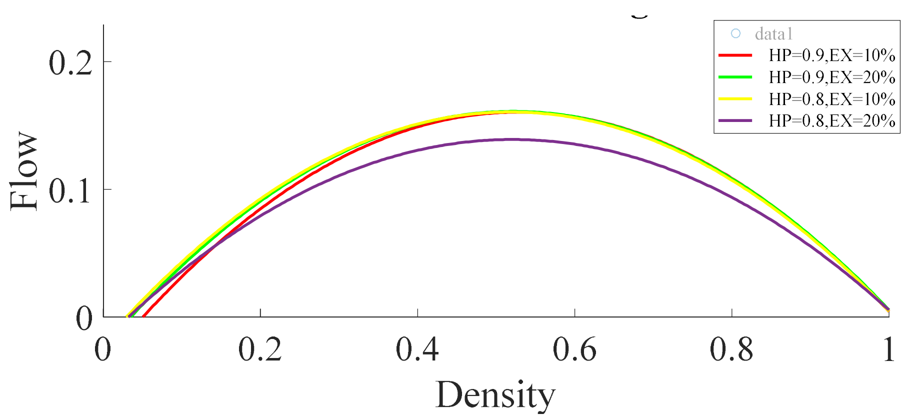


Figure 16: The fundamental diagrams of the normally distributed-ASEP model discussed section 2.2.1.1: flow in the model is plotted against the density of vehicles in the model. In this graph in the legend of diagram different specification have been explained where hopping probability of expert drivers is HP and percentage of expert drivers in the model is given by EX. Specifications of average drivers and amateur drivers were kept constant through the simulation.

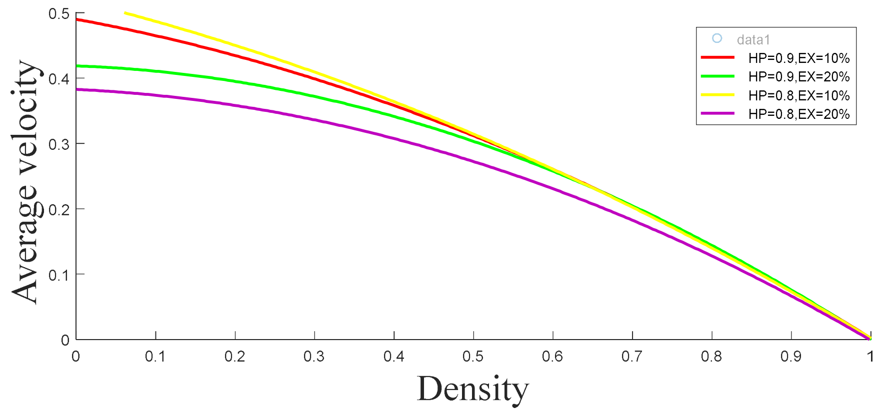


Figure 17: The Average velocity vs. density graph of the normally distributed-ASEP model discussed section 2.2.1.1: average velocity of all the drivers is plotted against the density of vehicles in the model. In this graph in the legend of diagram different specification have been explained where hopping probability expert drivers is HP and percentage of expert drivers in the model is given by EX. Specifications of average drivers and amateur drivers were kept constant through the simulation.

As shown in the Fig. 17, simulation results for variation in hopping probability and number of expert drivers have similar output in all different compositions discussed above. Only in the case of HP=0.8 and EX=20, there is a slight drop in flow and average velocity.

- Conclusion

Based on above results we can conclude that driving efficiency and number of expert drivers in the model have no effect or negligible effect on the performance of the system. Increase or decrease in driving efficiency of expert drivers does not lead to increase or decrease in system performance and therefore system performance does not depend on expert drivers.

3.1.1.2 Relationship between average drivers and the flow in the model

- Model

The aim of this set of simulation is to understand the correlation between average drivers and system performance. In order to do that in our simulation, we kept other variables constant,

Table 4: Specifications for simulation

Simulation set I (hopping probability variation)		
Drivers type	Composition	Hopping probability 1st , 2nd simulation
Expert Drivers	10 %	0.9
Average drivers	80 %	0.7, 0.6
Amateur drivers	10%	0.4
Simulation set II (composition variation variation)		
Drivers type	Composition 3rd, 4th simulation	Hopping probability
Expert Drivers	10 %	0.9,
Average drivers	80 %,60%	0.7
Amateur drivers	10%,	0.4

therefore in this set of simulations hopping probability and composition of amateur and expert drivers was kept constant whereas specifications of average drivers were varied in given limit. Simulations were carried out separately for hopping probability variation and composition variation. Specifications for different simulations are given in table 4.

- Results of simulation:

In this set of simulation also we compare four fundamental diagrams of above discussed simulation of the normally distributed-ASEP model. We also compared average velocity vs. density graph to see changes in individual performance. Simulation results were as shown in the Fig. 18 and Fig. 19. As shown in the figure simulation results for variation in hopping probability and number of average drivers have similar output in all different compositions discussed above. This is evident in the fundamental diagram as well as Avg. flow vs. density graph

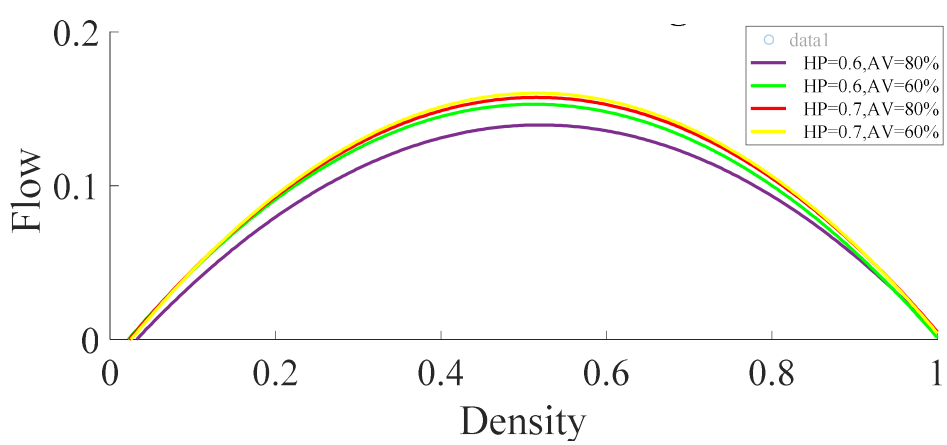


Figure 18: The fundamental diagrams of the normally distributed-ASEP model discussed section 2.2.1.2: flow in the model is plotted against the density of vehicles in the model. In this graph in the legend of diagram different specification have been explained where hopping probability of average drivers is HP and percentage of average drivers in the model is given by EX. Specifications of expert drivers and amateur drivers were kept constant through the simulation.

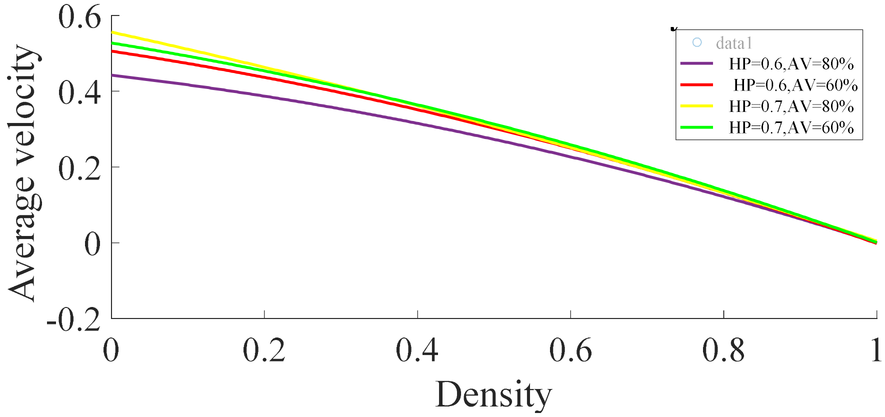


Figure 19: The Average velocity vs. density graph of the normally distributed-ASEP model discussed section 2.2.1.2: average velocity of all the drivers is plotted against the density of vehicles in the model. In this graph, in the legend of diagram different specification have been explained where hopping probability average drivers is HP and percentage of average drivers in the model is given by EX. Specifications of expert drivers and amateur drivers were kept constant through the simulation.

- Conclusion:

Based on above results we can conclude that driving efficiency and number of average drivers in the model have no effect or negligible effect on the performance of the system. Increase or decrease in driving efficiency of average drivers does not lead to increase or decrease in system performance and therefore system performance does not depend on average drivers.

3.1.1.3 Relationship between the amateur drivers and the flow in the model

- Model:

The aim of this set of simulation is to understand the correlation between amateur drivers and system performance. In order to do that in our simulation we kept other variables constant, therefore in this set of simulations hopping probability and composition of average and expert drivers was kept constant whereas specifications of amateur drivers were varied in given limit. Simulations were carried out separately for hopping probability variation and composition variation. Specifications for different simulations are given in table 5,

Table 5: Specifications for simulation

Simulation set I (hopping probability variation)		
Drivers type	Composition	Hopping probability 1^{st}, 2^{nd},3^{rd},4^{th},5^{th} simulation
Expert Drivers	10 %	0.9
Average drivers	80 %	0.7
Amateur drivers	10%	0.5,0.4,0.3,0.2,0.1

- Results of simulation:

In this set of simulation also we compare four fundamental diagrams of above discussed simulation of the normally distributed-ASEP model. We also compared average velocity vs. density graph to see changes in individual performance. Simulation results were as shown in the Fig. 20 and Fig. 21. In this set of simulation with a decrease of hopping probability of amateur drivers, a decrease in flow as well as average velocity was observed. The result from simulation was as shown in the figure below.

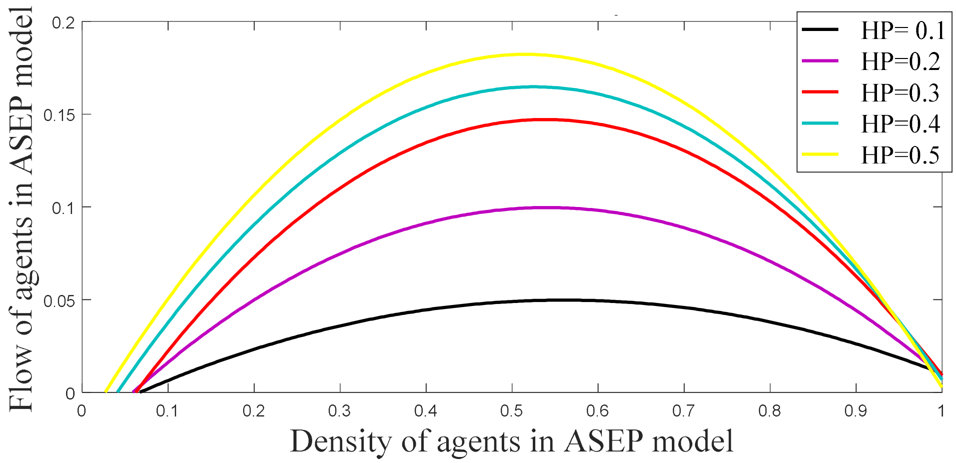


Figure 20: The fundamental diagrams of the normally distributed-ASEP model discussed section 2.2.1.3: flow in the model is plotted against the density of vehicles in the model. In this graph in the legend of diagram different specification have been explained where hopping probability of amateur drivers is HP. Specifications of expert drivers and average drivers were kept constant through the simulation.

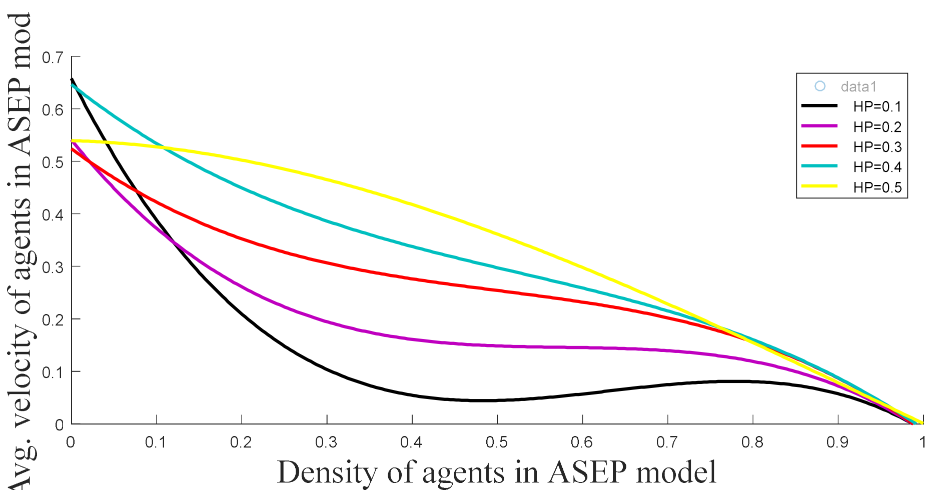


Figure 21: The Average velocity vs. density graph of the normally distributed-ASEP model discussed section 2.2.1.3: average velocity of all the drivers is plotted against the density of vehicles in the model. In this graph, in the legend of the diagram different specification have been explained where hopping probability the amateur drivers is HP. Specifications of expert drivers and average drivers were kept constant through the simulation.

- Conclusion

From the above observations, we can conclude that in normally distributed-ASEP model. The Flow as well as the average velocity of agents in model directly depends on the hopping probability of amateur drivers in the model. Therefore we can say that in the normally distributed-ASEP model, system performances depends on the driving efficiency of amateur drivers. Even with a small percentage of amateur drivers driving efficiency of the system is governed by the hopping probability of amateur drivers and hence driving efficiency of amateur drivers.

4 Single-Lane Unidirectional Highway Model: Analysis of traffic congestions in single-lane highway

4.1 Single-Lane Unidirectional Highway Model

In the normally distributed-ASEP model, we were able to introduce the diversity of drivers in the model. But there are many other features missing in normally distributed-ASEP model in order to represent highway transportation in a realistic way. As we have discussed previously in section 1.1.2, Based on fundamental diagrams from real life highway traffic, following characteristics of highway transportation were needs to be represented by simulation to, represent real life traffic system.

- Critical density (Cd) at around 20% of maximum model capacity

In the case of ASEP model with constant hopping probability, we have observed that change in phase, normally happens at 0.5 density value. But in the case of real life traffic jam, data have shown that this phase change usually happens at 0.2 values. As discussed earlier this change in phase occurs because of the instability in equilibrium in a system which leads to phantom jam on the highway. Phantom jams are traffic congestions that occur even without bottlenecks.

- Discrete single-step drop in flow and average velocity at critical density:

In ASEP model change in phase has smooth and continuous nature. This change in phase represents a change in flow and average density. On the other hand in real life traffic system, observed data has shown that change in flow and average velocity at critical density is not smooth or continuous. In fact, this change in flow has discrete one-step drop nature. Observed data have shown that, on the highway, at critical density flow in the system, discretely drops to 2/3 of maximum flow in the system.

- Absence of zero flow scenario

Data from highway observations have shown that even with 100% density, flow on highway never reduces to zero. Unless there is some serious situation such as road blockage or major accident which can completely block traffic on the highway there always will be forward movement and these serious situations happen rarely. Therefore zero flow scenarios are rare on the highway.

- Reverse-lambda shape of fundamental diagram:

After a change in phase from free flow to jamming phase, highway data have shown that there is the continuous decrease in the flow of vehicles in the highway system, all these characteristics combinedly lead to reverse-lambda nature of fundamental diagram. Schematics of the Fundamental diagram from real life highway traffic can be represented by the Fig 22. Fig. 22 also shows different characteristics of highway traffic that we discussed earlier.

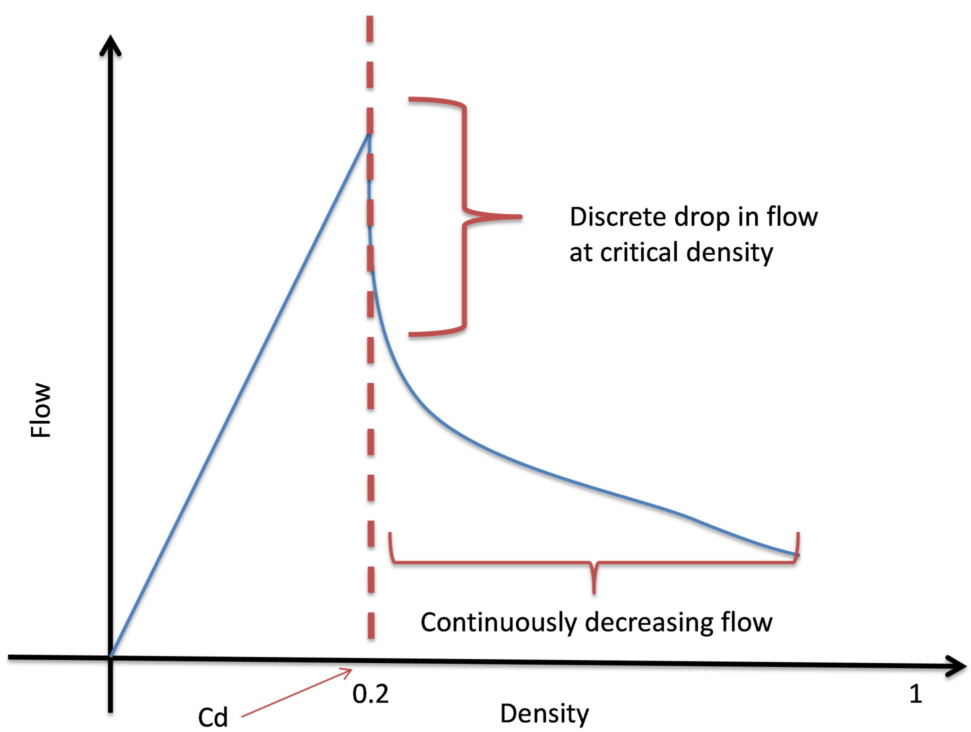


Figure 22: Schematic representation all the four characters of the highway traffic fundamental diagram. The fundamental diagram is the flow vs. density graph for highway traffic. Characteristics of the fundamental diagram: a) Critical density (Cd) at 0.2 density, b) Discrete drop in flow at the critical density, c) The continuous decrease of flow in jamming phase, d) Reverse-lambda shape of fundamental diagram.

- Models

The normal distributed-ASEP model is further extended into the single-lane unidirectional highway model (SLUHM). The SLUHM represents traffic on a single-lane highway. Observations have shown that in highway traffic critical density is around 20%value, therefore for highway traffic, jamming phase triggers when densities of vehicles on road reach to 20 % of its maximum value. Whenever density of vehicle in traffic system is more than 20% system is considered to be in jamming phase. Based on this information SLUHM was divided into two phases

- Free flow phase
- Jamming phase.

In free flow phase hindrances of surrounding environment on driving efficiency of drivers was assumed to be negligible thereby all drivers were assumed to be driving with high driving efficiency. This was represented by high hopping probability (HP=0.9) for all drivers. To represent jamming phase triggering action (critical density) in the SLUHM, the model was designed in such way that whenever density rises above the critical density, hopping probability of average drivers and amateur drivers would decrease. This represents a decline of driving efficiency of average and amateur drivers in the model. The hopping probability of average drivers was reduced to 0.7. While reduction in hopping probability of amateur driver is discussed in next section,

4.1.1.1 Single step drop in hopping probability

- Simulation specifications

This simulation was based on the common assumption that congestions are a static phenomenon and in traffic system at the critical density, there is only one single step drop in the driving efficiency therefore, in SLUHM as shown in Fig 23, at the critical density, this assumption was represented by single step drop in hopping probability of amateur drivers from 0.9 to 0.6. All the specifications for simulations were as shown in table 6. Change in hopping probability of amateur drivers with respect to density is as shown in Fig. 23.

Table 6: Specifications for simulation

Driver type	Free flow phase Hopping probability	Jamming phase Hopping probability
Expert drivers	0.9	0.9
Average drivers	0.9	0.7
Amateur drivers	0.9	0.6

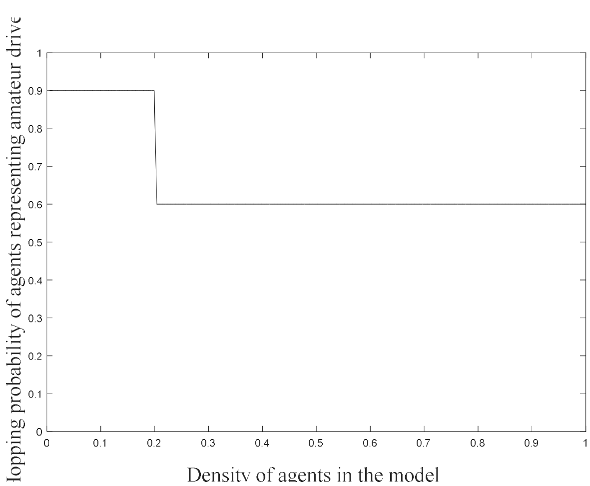


Figure 23: The changes in hopping probability for corresponding changes in the density are plotted for the single-step drop in hopping probability simulation.

- Simulation Result and Discussion

Simulation results of the SLUHM for single step drop in hopping probability was as shown in Fig. 24 and Fig. 25 As shown in Fig. 24 in the case of average velocity vs. density graph, at the critical density, discrete drop in average velocity was observed, as well as thereafter continuous decline in average velocity with an increase in density was also observed. On the other hand in case of the fundamental diagram as shown in Fig. 24, although discrete drop at critical density was seen but thereafter rise in the flow was observed. This rise resulted in the second critical density at density equals to 0.5.This behaviour of a two critical densities was not similar to real life data and did not lead to reverse-lambda behaviour that has been discussed in this chapter. Therefore, our assumption about a single step drop was proven to be false.

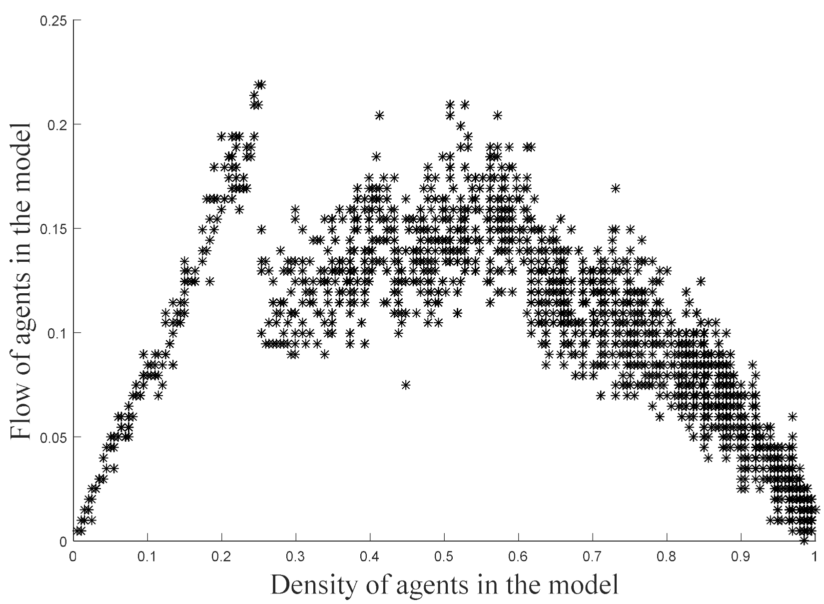


Figure 24: The fundamental diagram for single step-drop in hopping probability simulation: The flow in the model is plotted against the density of vehicles in the model.in this fundamental diagram, there are two critical densities when a change in phase occurs. This behaviour of two critical densities is not observed in the highway. Therefore this fundamental diagram does not represent highway traffic.

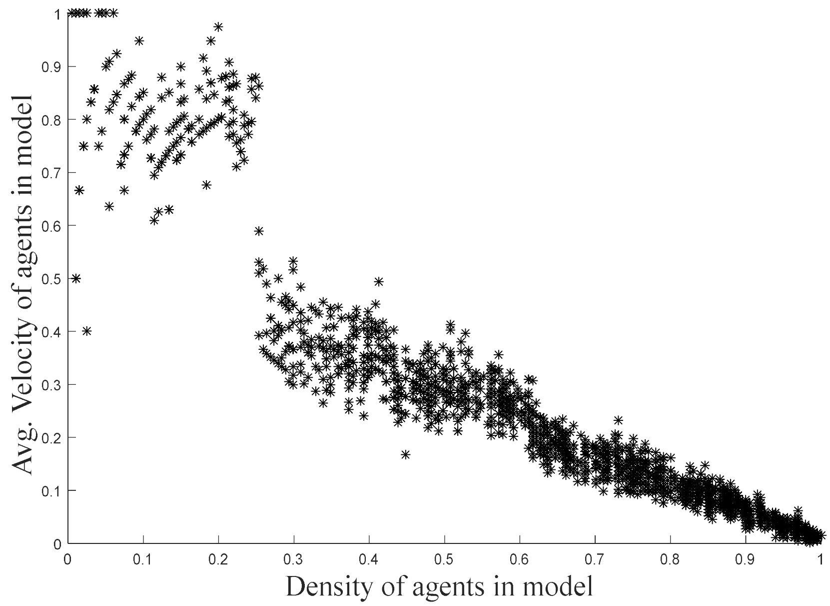


Figure 25: The average velocity vs density graph for single step-drop in hopping probability simulation: here average velocity of vehicles in plotted against the density of vehicles in the same model.

4.1.1.2 Linear decrease in hopping probability

- Model

In this strategy, we assumed other possibility where hopping probability of amateur drivers in jamming phase was assumed to be linearly decreasing. This assumption can be represented by equation 1 as well as fig, in equation 1 in order to produce a discrete drop of about 2/3 of maximum flow, the value of 'A' should be greater than 2.

$$Hopping\ probability = 1 - A \times Density\ \ for\ A \geq 2$$

as shown in Fig 26, at the critical density, hopping probability of amateur drivers decreases linearly with increase in density. All the specifications for simulations were as shown in table 7. Change in hopping probability of amateur drivers with respect to density was as shown in Fig. 26.

Table 7: Specifications for simulation

Driver type	Free flow phase Hopping probability	Jamming phase Hopping probability
Expert drivers	0.9	0.9
Average drivers	0.9	0.7
Amateur drivers	0.9	$Hopping\ Probability = 1 - A * Density$ $For\ A \geq 2$

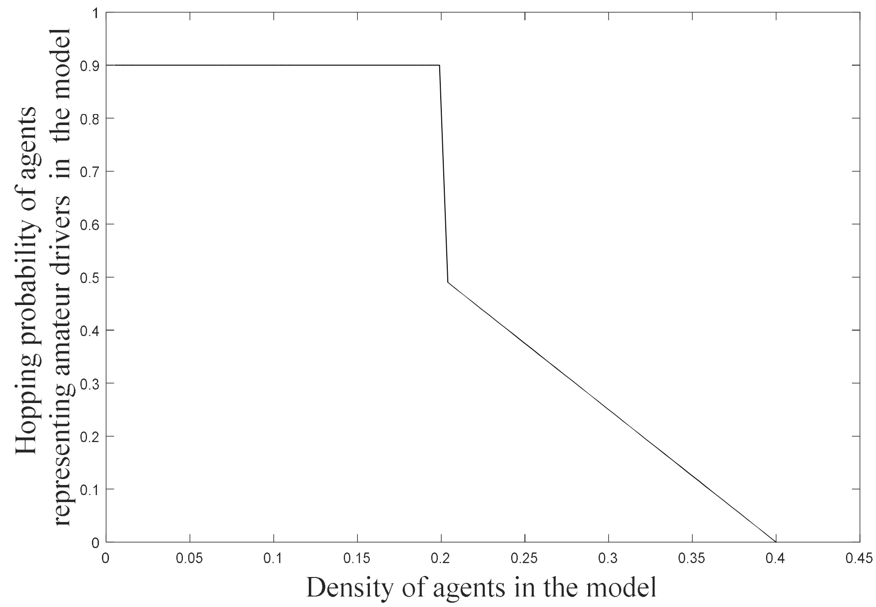


Figure 26: The changes in hopping probability for corresponding changes in the density are plotted for the linear decrease in hopping probability simulation. In this simulation hopping probability of amateur, drivers, decrease linearly in the jamming phase.

- Simulation result and discussion

Linearly decreasing hopping probability in SLUHM led us to the results as shown in Fig. 27 and Fig. 28 As shown in Fig. 27 and Fig. 28 at the critical density, discrete drop in average velocity and the flow were observed as well as, continuous decrease in average velocity in jamming phase was seen too, however for density = 1/A, the Hopping probability equation becomes zero, this leads to zero average velocity and therefore zero flow condition. This behaviour of zero flow condition is not similar to real life data where the zero flow condition is rare for density less than one. Therefore, our assumption about the linear decline in hopping probability was also proven wrong.

Figure 27: The fundamental diagram for the linear decrease in hopping probability simulation: The flow in the model is plotted against the density of vehicles in the model.in this fundamental diagram at the 0.4 density, the flow in model reduces to zero. This behaviour of two flow is not observed in the highway. Therefore this fundamental diagram does not represent highway traffic.

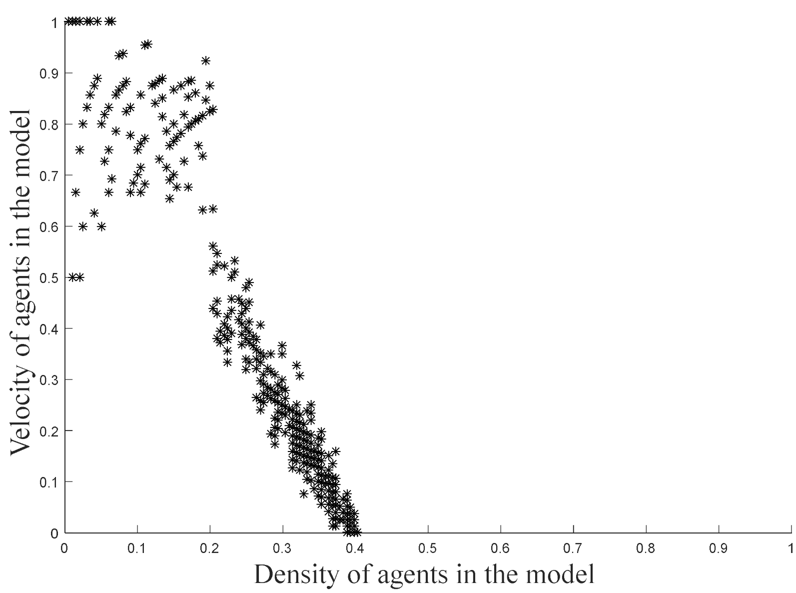


Figure 28: : The average velocity vs. density graph for the linear decrease in hopping probability simulation: The average velocity of vehicles in the model is plotted against density in the same model. In this graph at the 0.4 density, the average velocity of vehicles reduces zero.

4.1.1.3 Exponentially decaying hopping probability

- Model

In this strategy after the critical density, the hopping probability of amateur drivers was assumed to be exponentially decaying. This decaying relationship between hopping probability and density is represented by equation 2,

$$Hopping\ probability = A^{Density}\ \ for\ A < 1$$

During all these simulation driving efficiencies of expert, drivers were considered to be high and effect of density on it was assumed to negligible. This was represented by constant hopping probability of 0.9. As shown in Fig 29, after the critical density, hopping probability of amateur drivers decreases linearly with increase in density. All the specifications for simulations were as shown in table 8. Change in hopping probability of amateur drivers with respect to density is as shown in Fig. 29.

Table 8: Specifications for simulation

Driver type	Free flow phase Hopping probability	Jamming phase Hopping probability
Expert drivers	0.9	0.9
Average drivers	0.9	0.7
Amateur drivers	0.9	$Hopping\ Probability = A^{density}$ $For\ A < 1$

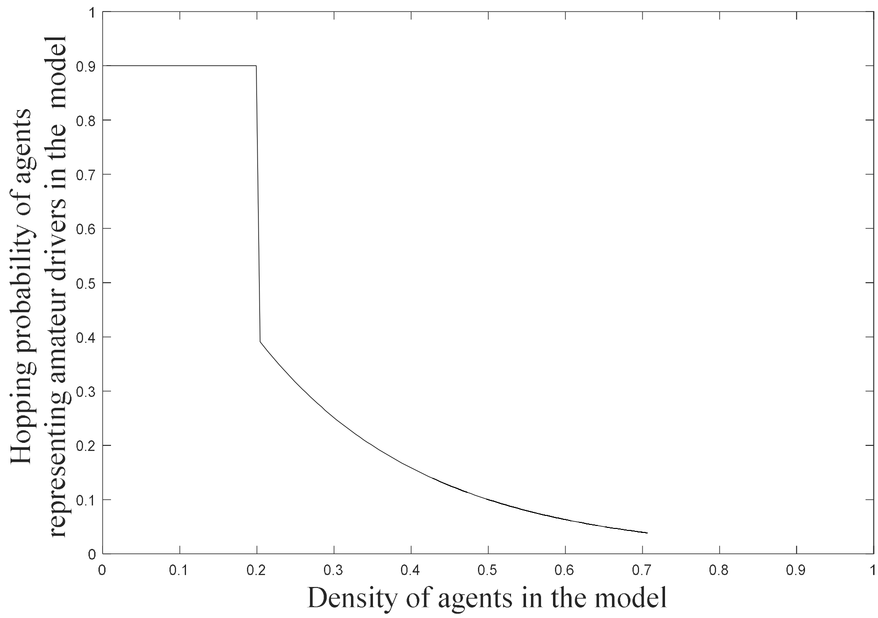


Figure 29: The changes in hopping probability for corresponding changes in the density are plotted for the exponentially decrease in hopping probability simulation. In this simulation hopping probability of amateur drivers decrease exponentially in the jamming phase.

Simulation results and discussion

Simulation results of SLUHM with exponentially decaying hopping probability are as shown in Fig. 30 and Fig.31. As shown in Fig. 31 at the critical density, discrete drop, as well as the continuous decay of average velocity in jamming phase, was observed. This resulted in the fundamental diagram was as shown in Fig. 30. This simulation was able to produce all characteristics of real life traffic congestions, for the value of ‘A’ < 0.05 the model had close similarity with real life data and other simulations. Therefore, we concluded that exponentially decaying hopping probability of amateur drivers in SLUHM, explains traffic congestions in the highway.

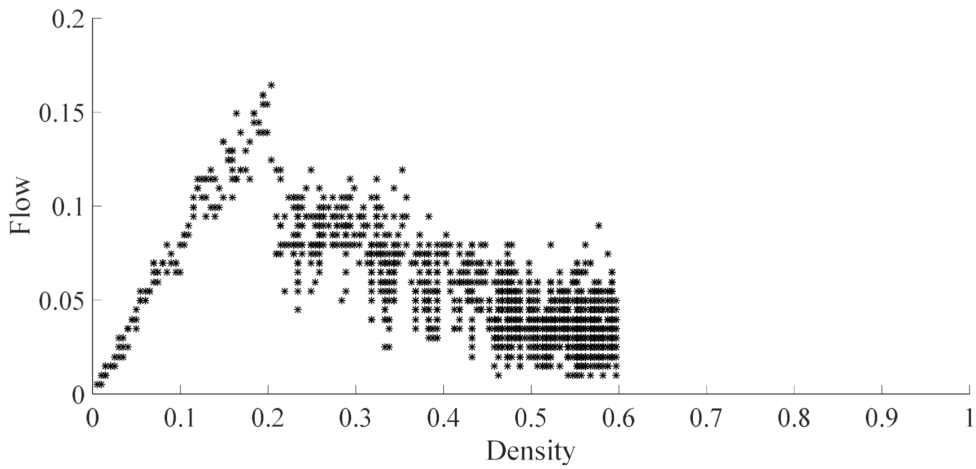


Figure 30: The fundamental diagram of exponential decrease in hopping probability simulation: The flow in the model is plotted against the density in the same model. This simulation exhibits all characteristics of the real life highway traffic.

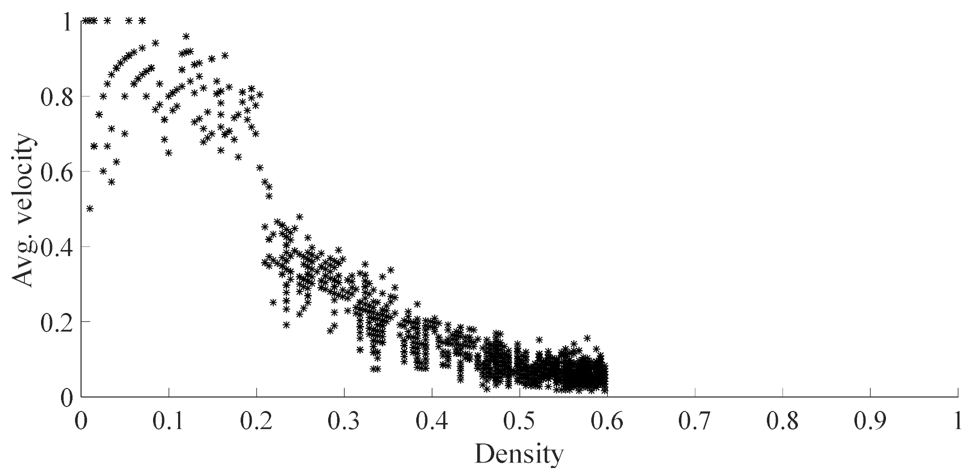
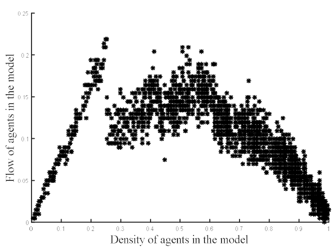
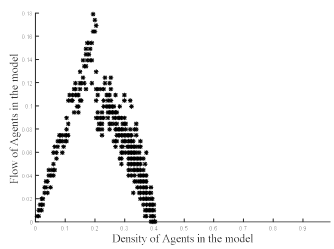
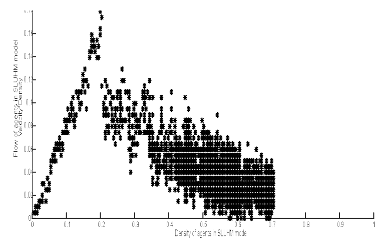
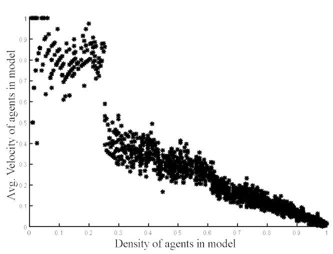
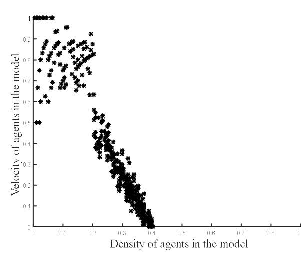
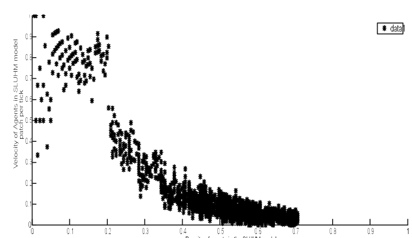


Figure 31: The average velocity vs. density graph of exponential decrease in hopping probability simulation: The average velocity in the model is plotted against the density in the same model. This simulation exhibits all characteristics of the real life highway traffic.

Table 9: Comparison between simulation results

Single step-drop in HP Simulation	Linear decrease in HP simulation	Exponentially decaying in HP Simulation
HP of amateur drivers in jamming phase = 0.6	HP of amateur drivers in jamming phase eq. $HP = 1 - A * Density$ $for\ A > 2$	HP of amateur drivers in jamming phase eq. $HP = A^{Density}$: A < 1
Fundamental diagram 	Fundamental diagram 	Fundamental diagram 
Avg. velocity vs. density 	Avg. velocity vs. density 	Avg. velocity vs. density 

Single step-drop in HP Simulation	Linear decrease in HP simulation	Exponentially decaying in HP Simulation
Discrete drop in the flow and the Average velocity at the critical density= OBSERVED	Discrete drop in the flow and the Average velocity at the critical density= OBSERVED	Discrete drop in the flow and the Average velocity at the critical density = OBSERVED
Continuous decreasing flow and average velocity in jamming phase = NOT OBSERVED: Continuous decrease in ave. velocity was observed but same was not observed in the case of flow	Continuous decreasing flow and average velocity in jamming phase = OBSERVED	Continuous decreasing flow and average velocity in jamming phase = OBSERVED
The absence of zero flow instant = OBSERVED	The absence of zero flow instant = NOT OBSERVED	The absence of zero flow instant = OBSERVED

Single step-drop in HP Simulation	Linear decrease in HP simulation	Exponentially decaying in HP Simulation
Reverse-lambda behaviour of fundamental diagram= NOT OBSERVED	Reverse-lambda behaviour of fundamental diagram = OBSERVED	Reverse-lambda behaviour of fundamental diagram = OBSERVED
Conclusion = DOES NOT REPRESENT HIGHWAY TRANSPORTATION FLOW IN REALISTICALLY WAY	Conclusion = DOES NOT REPRESENT HIGHWAY TRANSPORTATION FLOW IN REALISTICALLY WAY	Conclusion= REPRESENTS HIGHWAY TRANSPORTATION FLOW IN REALISTIC WAY

4.1.2 CONCLUSION:

After multiple simulations with different specifications, we propose single-lane unidirectional highway model. In the proposed single-lane unidirectional highway model (SLUHM), flow in the model is governed by hopping probability of amateur drivers. After critical density, decadent nature of hopping probability of same drivers explains the continuous decrease in average velocity as well as traffic flow with increase in density of vehicles in the model. Based on the above analysis, we concluded that contrary to common belief traffic congestions are dynamic phenomena; where the flow of vehicles on the highway is governed by driving efficiency of the amateur drivers. The driving efficiency of amateur drivers deteriorates with an increase in density. This leads to decrease in driving performance of all drivers. This deterioration has an exponentially decaying characteristic. The reasons behind this deterioration have a psychological and social origin.

4.2 Comparison of Highway Traffic and Foraging Ant traffic

In this study, the ASEP model extension has been used to realise traffic on the highway. As we know same ASEP model is extended to represent the ant traffic in the ant-trail model, therefore the base of both these models is the same ASEP model; hence by comparing these two models we can compare highway traffic and ant traffic using same parameters, in the similarly controlled environment. The table 10 below shows a comparison between highway traffic and ant traffic.

Table 10: Comparison between highway traffic and foraging ant traffic

Highway Traffic	Ant Traffic
Represented by SLUHM	Represented by Ant-trail model (Nishinari et al)
Communication though visual information: ambigues	Communication though chemical information: precise
The fundamental diagram	
Critical density in the highway is around 20 % of the maximum density of vehicles on the highway.	Critical density in the ant traffic is around 75 % of the maximum density of ant on the trail.
Free Flow phase on the highway is up to 20 % of the maximum density of vehicles on the highway, where flow on the highway increases with increase in density.	Free Flow phase in ant trail is up to around 75 % of the maximum density of ants in the trail, where flow in ant traffic increases with increase in density.

Jamming phase triggers at 20% of maximum density	Although, according to observation ant traffic system avoids jamming phase, therefore, based on observation there is no jamming phase in ant traffic, but ant-trail simulation shows that in ant trail critical density is around 75 % and jamming phase triggers at around critical density.
Apart from small free flow phase, flow on the highway decreases with increase in density of vehicles.	Flow in ant trail increases with increase in density of ants.
Velocity vs. Density	
On the highway, after small free flow phase, the average velocity of drivers continuously decreases with corresponding increase in density of vehicles.	In ant trail, the velocity of ants remains constant with negligible drop irrespective of the density of ants.
In highway traffic, an increase in density of vehicles leads to increase in hindrance for drivers, therefore a decrease in driving efficiency of drivers on the highway.	In ant trail, an increase in density of ants contributes to increase in information quantity and quality in communication which ultimately leads to increase in efficiency of ants.
In highway traffic deviation in velocity from average value is independent of density.	In ant traffic deviation in velocity from average value decreases with increase in density.

Conclusion: Performance of drivers on highway decreases with increase in density. This happen because with increase in density information thought visual communication does not show significant improvement in information quality, therefore increase in density act as hinderence and hence flow decreas with increase in density	Conclusion: Performance of ant in trail increases with increase in density. This happen because, increase in density lead to increase in quality of information though chemical communication , which is used for improvement of average velocity in trail as well as to keep density in check.

4.3 Conclusion of comparison

On a highway with an increase in the number of vehicles, a hindrance for drivers increases. This increase in hindrance leads to decrease in a driving performance of drivers, therefore with an increase in density of vehicles, a flow and a velocity of drivers on a highway decrease. On the other hand, due to the better communication strategy, ants in trail manage to avoid traffic jams on the trail. Ants use communication system through which they provide an information about the density and the optimum velocity to all worker ants. by using this information ants manages to control the density of ants on the trail. At the same time, with the combined information of density and average velocity ant manages to reduce deviations in velocity with an increase in density. Therefore due to the communication of density and optimum velocity the flow of ant in trail increase with an increase in density of ants and also the velocity of ants does not depend on a number of ants in the trail.

This led us to the conclusion that although, highway traffic and ant traffic have the same basic system; in a similar environment, ants manages to establish a better communication system to provide information about the density and optimum velocity. This communication system helps them to avoid traffic congestion on ant trail and due to the similar basis by implementing similar communication strategy, a highway traffic can improve the flow of vehicles on the highway.

5 CONCEPTUAL SYSTEM DESIGN: INTELLIGENT TRANSPORTATION SYSTEM BASED ON BIOMIMICRY OF FORAGING ANTS

As discussed in the previous section, an ant transportation system and a highway traffic have a similar basic transportation system, but due to information about the number of ants in the trail and optimum velocity, ants manage to avoid traffic congestion in the trail. At the same time, with the same information, ant's system helps them to keep their velocities optimum and independent of numbers of ants on the trail, also with an increase in density this information becomes better and therefore variation in velocity is also reduced with density. On the other hand in highway traffic, lack of communication leads to a hindrance for drivers on the road. This hindrance leads to decrease in flow and velocity of vehicles which results in traffic congestion. To counter above scenario, in this chapter, we are introducing the concept of "The Biomimicry of Ant-Trail-Intelligent Transportation System (BAT-ITS)". This system is based on biomimicry of foraging ant. This intelligent system will help us to regulate traffic flow on the highway.

Currently. In the commercial market, automation in the automobile industry is at level-3 but in the following section, for the reason of simplicity, we are only concentrating on system description of level-5 automated vehicles that will be compatible in automated transportation system. Considering the number of interfaces and complexity of transportation system, it will be logical to use system engineering for system design. Considering this factor in mind we are using 'SysML' model to explain given system.

At level 5 automation cars will be capable of full automation and will be capable of decision making to the fullest. In this kind of automation scenario, BAT-ITS will be a small sub-system of complicated and huge navigation system. unfortunately, currently, there is no system model that explain level 5 automation and hence the complete design of BAT-ITS will be inappropriate. Considering this restriction, in this thesis, we are only proposing conceptual system design. This conceptual system design will only explain important strategies to prevent traffic congestion. In the future with further improvement in automation and further experimental verification and validation, this conceptual design can be modified in the complete system design which will be compatible with other sub-systems.

5.1 Requirement analysis

For the most of the transportation systems, as we discussed earlier, traffic congestion has a variety of adverse effect. Therefore for transportation system as shown in Fig. 32 “Reducing traffic congestion” is a high-level requirement. This requirement of “Reducing traffic congestion” can further refine as “Reduction of time wastage in travel”. Now above requirement of “Reduction of time wastage in travel” is different for different stakeholders. Currently, in our system, we have considered only two important stakeholders i.e., passengers and transport governing body (Transport Ministry etc.). based on traffic flow analysis is chapter 3, from the passengers’ perspective, reduction of time wastage in travel can simply achieve by keeping average velocity high, therefore for passengers on given road the above requirement is extended as “Keep average velocity as high as possible”. Whereas from same analysis, for transportation governing bodies’ point of view which we also called as system point of view, reduction of time wastage can further extend as “keep the flow of vehicles as high as possible”. Although these two requirements are for different stakeholders, they are related to each other and can be achieved simultaneously. Requirement diagrams for BAT-ITS is as shown in Fig. 32 and Fig. 33

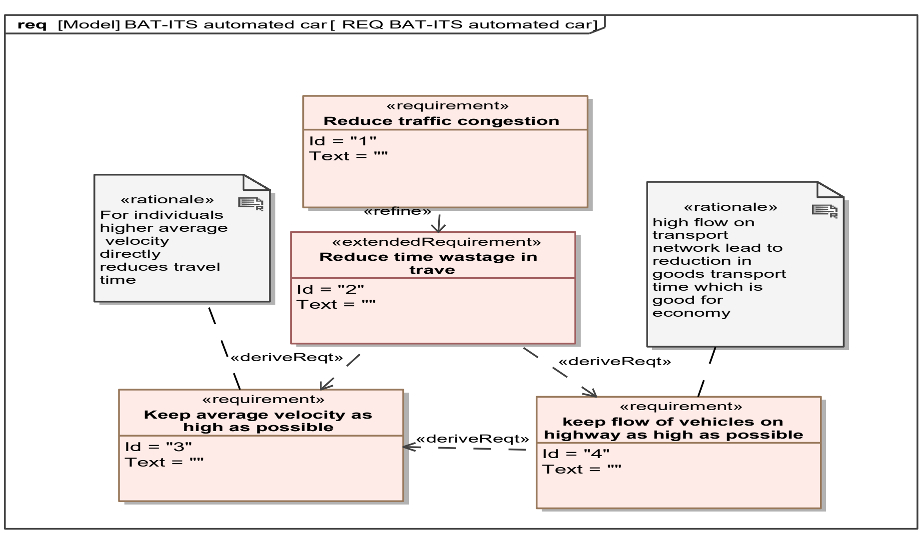


Figure 32: The requirement diagram of BAT-ITS for general perspective

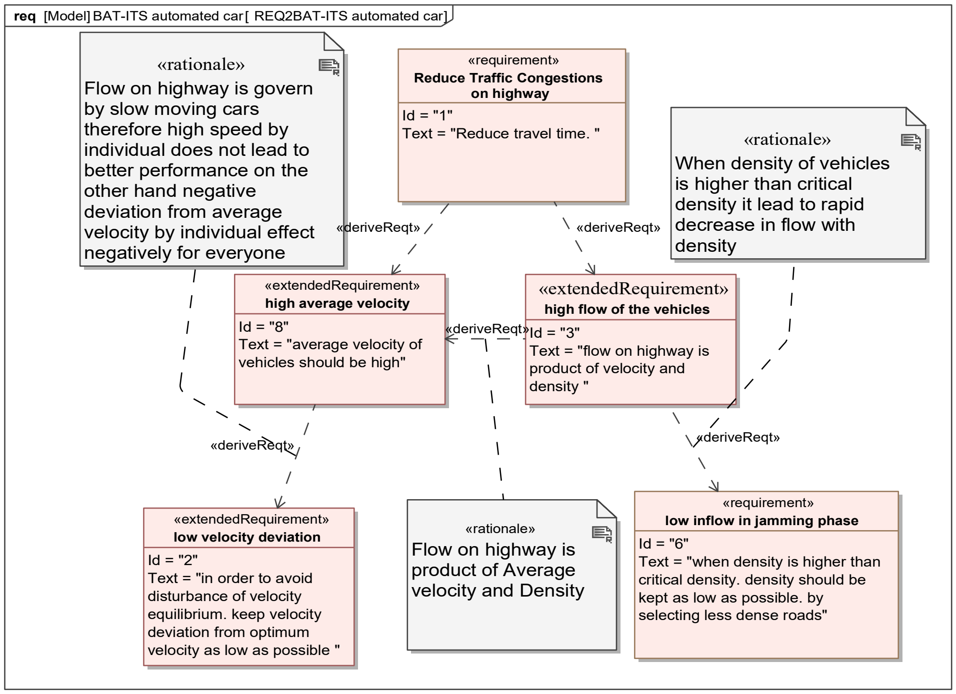


Figure 33: The requirement diagram of BAT-ITS from automobile manufacturer's perspective.

Fig. 32 gives a simple explanation about requirements in BAT-ITS system but for the purpose of further simplicity, in this study we are only concentrating on automobile system design which will be compatible with above mention system. Therefore Fig.33 explains requirement analysis from the perspective of automobile manufacturers to design the adaptive cruise control. As shown in a Fig. 33 similar to Fig. 32, requirement analysis starts at the top level requirement as "Reduce traffic congestion". Finally based on the comparison of ant traffic and highway traffic system requirements can be given as follow,

1) Reduce deviation from average velocity
2) in the case of density higher than the critical density, reduce the inflow of vehicles in highway (to manage density as close to critical density as possible)

5.2 Block Definition Diagram for BAT-ITS domain

Conceptual system level block definition diagram for BAT-ITS domain is as shown in Fig. 34. As shown in Fig. 34 BAT-ITS will be consist of main sub-level as follow

5.2.1 Environment

For the BAT-ITS domain, the BAT-ITS has to interact with the environment on all levels. The environment consists of many things such as road, other vehicles, traffic signal etc. A vehicle in a highway interacts with its environment and its movements depends on that interactions. Although The environment on the highway has multiple elements in it and it keeps on changing, but considering the purpose of our model, interaction of automated vehicle with road and preceding vehicles are only strategically important interactions, therefore for the purpose of simplicity, we have decided to mention only those two elements in our model.

5.2.2 Passenger:

Passengers are an important part of BAT-ITS domain. In fact, for urban transportation systems, passengers are the entity which is supposed to be transported.passengers will interact with BAT-ITS in multiple scenarios. One of such scenario is when a passenger will provide information about the destination.

5.2.3 Information and communication technologies (ICT):

BAT-ITS will be part of the much larger complex system, therefore, it will continuously interact with different systems. BAT-ITS will collect information from the different system. also, it will provide information. This task will be carried out with the help of ICTs. An example of this kind of systems will be satellite or cell phone etc.

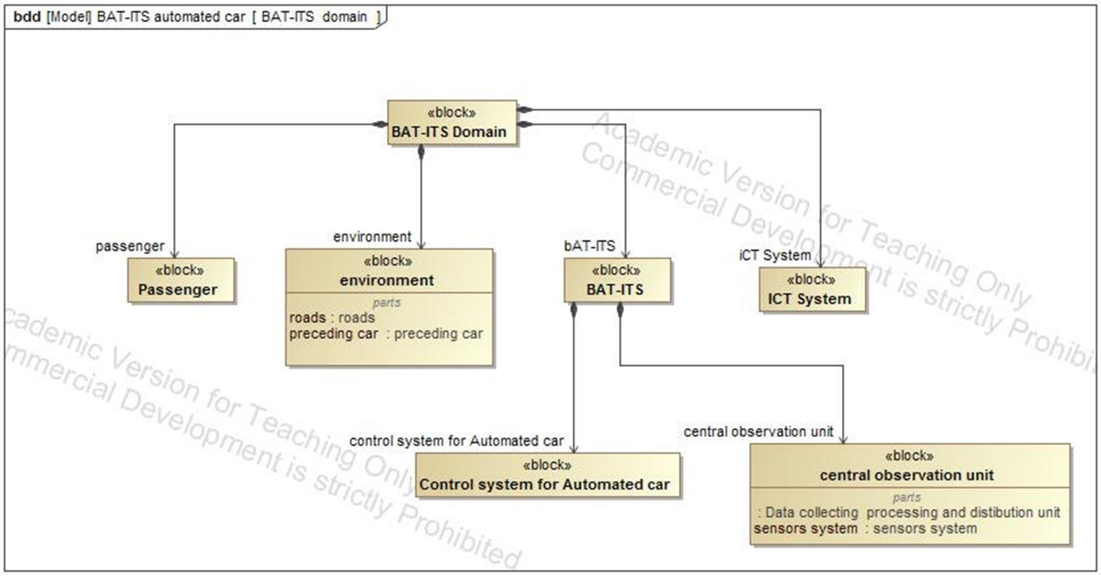


Figure 34: The Block definition diagram of BAT-ITS from automobile manufacturer's perspective

5.2.4 BAT-ITS:

BAT-ITS will be a collaboration of transportation governing body such as transport ministry with the automobile industry. Transportation governing body will be managing tasks such as information collection, processing and distribution, whereas automobile industry should be involved in the creation of automobile controlling system which can receive that information and use it to better transportation. Control system for the automated car. Therefore as shown in Fig. 34 BAT-ITS can further divided into two parts as follow,

- Control Observation Unite
- Control System for Automated Cat

5.3 Activity diagram

As we discussed in requirement analysis there are two different scenarios, where the intelligent car in BAT-ITS system needs to carry out two main strategic tasks simultaneously. We have used activity diagrams to explain the different activity in those two tasks. Due to their simultaneous nature both activities are explained in single activity diagram but for simplicity purpose in this article, we are explaining those two activities separately. Activity diagram for BAT-ITS is as shown in Fig. 35.

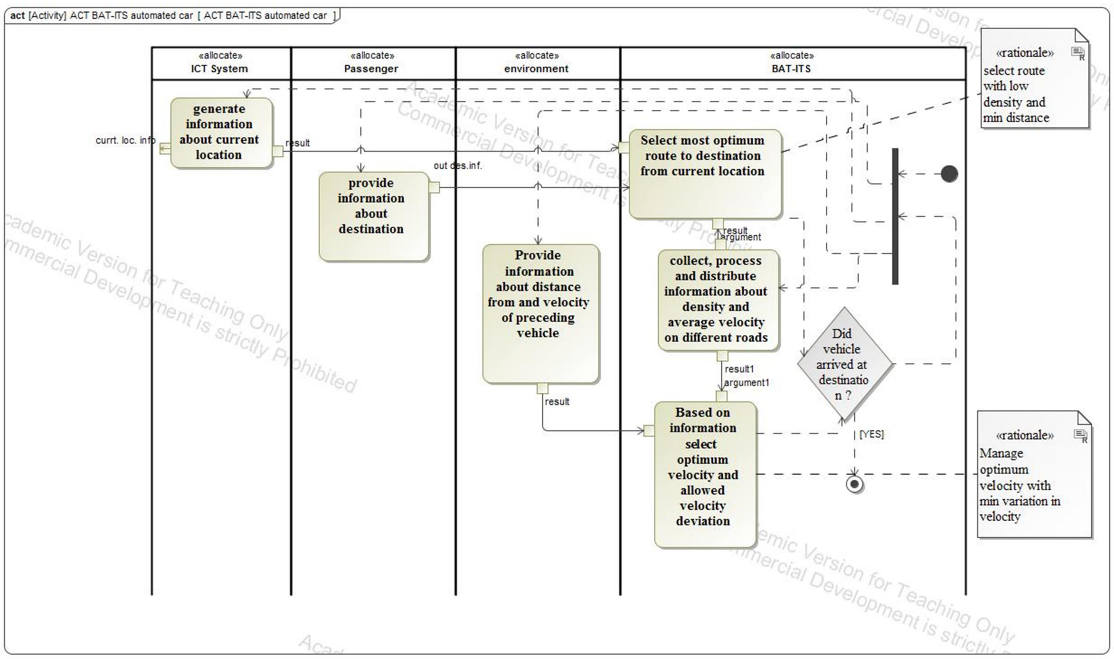


Figure 35: The activity diagram of BAT-ITS Intelligent car for two strategic activity of road selection and velocity selection.

5.3.1 Road selection: activity diagram:

The purpose of this activity is to select most efficient route connecting current location and destination. In this activity, intelligent car collects information about a destination from passengers and generate information about a current location by itself. After that, the intelligent car collects information about density on different roads connecting cars current position and destination. Based on information from different COUs of different road cars analyse which road is in free flow phase and which road is in jamming phase if roads with free flow phase are available, intelligent car selects one of the roads with free flow phase and shortest distance to destination. Whereas in the case of jamming phase intelligent car selects road that has low density and shortest distance to destination. This whole process of selection of road is adaptive and repeated continuously with new updated data till passenger reach the destination. By doing this car manages to travel with high average velocity and shortest distance. Therefore time wastage in travelling is reduced. Also due to high average velocity flow on highway remains high. Activity diagram for above activity is in Fig 35.

5.3.2 Velocity selection: activity diagram:

The purpose of this activity is to select the velocity and allowed velocity deviation, which will give optimum time and fuel performance on given road. In this activity route to the destination is from current information is decided therefore system concentrates on establishing high flow in the system. in order to do that, intelligent car collects information about the density and average velocity from COU of the current road, at the same time it collects information about the 'distance from' and velocity of preceding car. Based on this two information, intelligent car decides an optimum velocity and allowed deviation in velocity. With the help of this activity, the system manages to have less variation in velocity which ultimately helps in regulating flow in system and travel with optimum velocity.

6 CONCLUSION

In this thesis, we have compared the traffic flow analysis of highway traffic with the traffic flow of foraging ants. We have used an agent-based modelling to analyse the correlation between traffic congestion and movement efficiency of vehicles or ants in the corresponding transportation systems. Based on this analysis we have proposed the concept of a communication-based intelligent transportation system which will regulate the traffic flow in a highway transportation system.

In our study, we have proposed an agent-based model of the single-lane unidirectional highway traffic to analyse the emergent phenomenon of traffic congestion on the highway. With the help of this model, we have found that flow of vehicles on a highway is governed by driving efficiency of amateur drivers. In traffic congestion, decadent nature of driving efficiency of same drivers explains the continuous decrease in average velocity as well as traffic flow with increase in the number of vehicles on the highway. Based on the above analysis, we concluded that contrary to common belief traffic congestions are dynamic phenomena; where the flow of vehicles on the highway is governed by driving efficiency of the amateur drivers. The driving efficiency of amateur drivers deteriorates with an increase in the number of vehicles on a highway. This leads to decrease in driving performance of all drivers on the given highway. This deterioration of driving efficiency has an exponentially decaying characteristic.

In the latter part of our study, we have compared results of above simulation with simulation results of an already proposed model of ant-trail. Based on this comparison we have found out that, even with similar transportation strategy, contrary to highway traffic, the ant-trail system manages to avoid traffic congestion in the trail (Ant-trail system uses chemical communication to provide information about the density and optimum velocity to individual ants on the trail).

Based on the conclusion of above comparison, we have proposed the concept of the communication-based intelligent transportation system. By using collaboration between intelligent vehicles and central observation unit, this system will manage traffic flow from multiple points of views. By providing information about the density of vehicles on the highway this intelligent system will increase the flow of vehicles in the highway. At the same time by providing information about average velocity it will help the intelligent vehicle to manage optimum velocity in the highway. In future, this conceptual intelligent transportation system can be further developed and combine with other strategies for real life traffic application. It can also be modified for solving traffic congestions in other traffic like systems.

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8 REFERENCES

[1] INRIX 2015 Traffic Scorecard annual report [Online]. Available: inrix.com/scorecard/

[2] D. Helbing, Rev. Mod. Phys. 73 (2001) 1067.

[3] Chaudhuri D, Nagar A. Absence of jamming in ant trails: Feedback control of self-propulsion and noise. Physical Review E 2015;91(1):012706.

[4] Chowdhury D, Guttal V, Nishinari K, Schadschneider A. A cellular-automata model of flow in ant trails: Non-monotonic variation of speed with density. Journal of Physics A: Mathematical and General 2002;35(41):L573.

[5] Chowdhury D, Schadschneider A, Nishinari K. Physics of transport and traffic phenomena in biology: From molecular motors and cells to organisms. Physics of Life Reviews 2005;2(4):318-52.

[6] Couzin ID, Franks NR. Self-organized lane formation and optimized traffic flow in army ants. Proc Biol Sci 2003 Jan 22;270(1511):139-46.

[7] John A, Schadschneider A, Chowdhury D, Nishinari K. Trafficlike collective movement of ants on trails: Absence of a jammed phase. Phys Rev Lett 2009;102(10):108001.

[8] John A, Schadschneider A, Chowdhury D, Nishinari K. Collective effects in traffic on bi-directional ant trails. J Theor Biol 2004;231(2):279-85.

[9] Nishinari K. Jamology: Physics of self-driven particles and toward solution of all jams. In: Distributed autonomous robotic systems 8. Springer; 2009. .

[10] Nishinari K, Chowdhury D, Schadschneider A. Cluster formation and anomalous fundamental diagram in an ant-trail model. Physical Review E 2003;67(3):036120.

[11] Nishinari K, Sugawara K, Kazama T, Schadschneider A, Chowdhury D. Modelling of self-driven particles: Foraging ants and pedestrians. Physica A: Statistical Mechanics and its Applications 2006;372(1):132-41.

[12] TOMOEDA A. Unified analysis on shock wave formation in traffic jam. 2008.

[13] Wilensky, U. 1999. NetLogo. http://ccl.northwestern.edu/netlogo/. Center for Connected Learning and Computer-Based Modeling, Northwestern University. Evanston, IL.