Modelling, Simulation and Optimization for Motorway Vehicles

***Abstract*— The use of autonomous vehicles has increased in past few years. Traffic congestion is a severe problem faced my many countries. In this paper, the simulation model is implemented for motorway vehicles. The study is divided into three different parts. The model achieves the throughput of 174 Cars/Hour when simulated on multi-lane multiple vehicles with lane changing behavior. T_{opt} is 52.43 s. The density of the model is 3.32. Throughput obtained for rigid trucks is 95.84 Cars/Hour and cars is 95.94 Cars/Hour.**

Keywords*— *Simulation, Throughput, recorder, Lane, Entity, Vehicles.

I. Introduction

Modes of Transports have evolved significantly from the 1800s to the 2000s. As the Technological innovations and manufacturing power increased different modes of transport facilities were made available. From bullock carts to Fully Automated Cars is the journey that has been seen by the world. Prominent use of cars increased after the mid-1900s. Faster Production process and Technology evolution improved the performance, increased the availability to procure the demand, and reduced the cost of manufacturing. As per the report of Green Cars, there are 1.4 billion vehicles in the world and this number would double by the year 2040.

This humongous number of vehicles would result in the critical and recurrent problem of traffic congestions. The current situation of traffic congestion is not good as well. World prominent cities are facing the traffic congestion of more than 44%, i.e, To reach a particular distance it would need 44% or more time than on a normal uncongested road. The emergence of Automated vehicles also adds up to the severity of the problem[7]. Thus, there is a need for a solution that will accurately model, efficiently simulate, optimize according to the current traffic environment. Trinity College Dublin came up with a traffic management system that could self-organize. That means all the decision-making process is done by the simulation system on its own without any external influence.

We have replicated the research methodology of the above research by creating a Traffic Simulation Model. This model is developed using different python libraries such as Scipy Stats, SimPy V4, pandas, matplotlib, math, random. SimPy is a simulation framework that handles process-based discrete events that are built on the standard Python.

In this research, we aim to model a motorway environment that is divided into 3 separate parts.

The first part contains two simulations for two different kinds of vehicles i.e., Rigid Truck and Car separately. These two types of vehicles are prominently observed on a motorway, other vehicles can be studied as well but for this paper, we will be working with these two types of vehicles.

Here total Length of the motorway is 5000 meters that are incremented by a block of 1000 m.

The number of Lanes is 2.

The number of Cars is 50.

Inter Arrival Time is 10 Seconds.

The environment is recorded for 3000 seconds at each 1-second interval.

The second part contains a simulation of multiple cars on the motorway, this allows us to simulate the real-world motorway environment where multiple types of cars with their different specifications and attributes can be observed.

Here total Length of the motorway is 3000 meters that are incremented by the block of 1000 m.

The number of Lanes is 2.

The number of Cars is 400.

Inter Arrival Time is 30 Seconds.

The environment is recorded for 1000 seconds at each 1-second interval.

The third part of the Simulation study incorporates the lane merging behavior of a motorway. This is important as in real-world scenarios there are various possibilities due to which particular lane could be stopped at one particular point such as the incident of accident, maintenance work, traffic congestion on the opposite side of the road. Also, the lane could be ended naturally at a particular point. We often see that when this scenario occurs in the real world there would be congestion at the point of lane merging.

Here total Length of the motorway is 3000 meters that are incremented by a block of 1000 m.

The number of Lanes is 3 for the first 2000 m and 2 for 1000 m.

The number of Cars is 400.

Inter Arrival Time is 30 Seconds.

The environment is recorded for 1000 seconds at each 1-second interval.

The primary goals of the study are to find out t_{opt} Average Travelling Time in the non-congested and free-flowing traffic environment. What is the amount of optimum throughput N_{opt} cars/hours when the average travel time is 20% longer than t_{opt}. When traffic is congested but it is free-flowing, what is the maximum throughput N_{cong}. We are also interested in finding the influence of different kinds of Vehicles with their different acceleration and deacceleration characteristics. Also, how the model performs when a different mix of cars is simulated together.

The paper is structured in the following manner. Section I contains an introduction of the topic. Relevant Literature is reviewed in section II. The methodology used in model building is described in section III. Section IV, contains a simulation study according to different model parts. The obtained results and their qualitative evaluation and interpretation is explained in section V.

II. Literature Review

The specifications of the vehicle significantly differ for different variety of vehicles. For example, the time taken for an electric car to stop, braking capacity, acceleration, length, time taken to change lanes would be different for Rigid Truck, Articulated Vehicles. Now we will look at the literature reviewed to find out the relevant parameters related to vehicles and driving conditions and rules.

According to the report of Road Safety Ireland [1] and European Modular System (EMS) [2], the length for the Rigid Truck length varies between 12m to 20m. The articulated vehicle can range from 16.5 m to 25m. Two Axel Bus can have a length of 14 m. The average length of the Family Car is 5m. The length of a small electric car ranges from 2.6 m to 4.5 m.

The research conducted by [3] focuses on determining lane change behavior and time taken for lane change for different types of cars. For Cars as being shortest takes the least time to change the lane. As the car length increases the lane change time increases. 4, 8.9, 10.3, 9.1 seconds are the time taken by cars, LCV (light commercial vehicle), Heavy Vehicles and Bus. Similar research is conducted by research [4] but the result achieved is not similar to the previous study. The mean time to lane change cars and heavy vehicles is 4.6 and 3.8 seconds respectively.

Critical time tolerance is one of the factors that are important when performing simulation for the motorway. There are multiple rules which are used depending on the type of vehicle, nature of the road and environmental conditions. The report [5] suggests that on a normal road with no harsh environmental conditions 2 seconds rule is applied i.e., there should 2 seconds distance between car and car in front. So that there would be enough distance between two cars to stop without the crash. This rule can vary according to the country as well. Some countries follow, the 2-second rule for small cars, 4 Seconds rule for Medium vehicles and the 6-second rule for Heavy Vehicles.

The distance between the Front Right Lane vehicle and Back Right Lane vehicle is checked before starting the lane change process. Thus, it is necessary to use appropriate values for these two parameters. These distances vary according to car length and type. The smaller, lighter and faster the car this distance would be small in comparison to a large, heavy and slow car.

There are certain rules which are dependent on vehicle type. On a particular type of road, not all cars can run at the same maximum allowed speeds. The maximum allowed speeds for cars is 120 km/hour, Trucks and Heavy vehicles are 90, 100 km/hour respectively. According to a study of the Road Safety Authority on the motorway, different vehicles operate at different speed distributions. We have taken those quantile values of Cars, Rigid Truck and Articulated Vehicles [6].

III. Methodology

In the previous section, we reviewed the different research that would help us decide different parameters for the model building. Now we look at the structure of the model Implemented.

A. Packages

The methodology begins with importing necessary python libraries. These libraries are imported by creating the different Alias of the library. After that, we create the isZero function that will be used several times to check whether any particular variable is zero or no. The next step is to declare the Global variables. These variables are present in the entity block. These variables contain parameters that are vehicle-related and general traffic rules.

B. Entity

For the first part of the study, these variables are declared at the beginning but when simulating for different vehicle types, we declared them separately by creating additional code blocks. Further, simulation is divided into 5 different blocks. Lane, Vehicle, Property Surround, Recorder, Verification. The purpose of these blocks are different from each other; implementation of these blocks creates the base for the simulation model.

C. Lane

Lane class is used to describes the block/segment of Lane. If there is a single lane created then overtaking is not allowed. The segment of lanes is concatenated to form a complete lane. For example. If we want a 5 km motorway, we can create 5 lane segments of 1km each and join them. Also, these lane segments can be widened to build a multilane structure. That means it will attach the block of the lane sidewise. Lanes have a function that contains the state of the vehicle which is present on the lane at a particular time on the lane segment.

D. Vehicle

The next block is Vehicle, which contains the class vehicle to perform different operations such as braking, acceleration/velocity, wait, lane change from slow to the fast lane, from fast to slow lane. Also, it contains functions to check whether the car in front, front away right-left lane or back, back away right-left lane is slower or faster than your car. Also, there is a surround class that helps us locate whether there is a presence of other cars with respect to one car in the immediate vicinity.

E. Recorder

Now we will look at the code block that is important for us to visualize and understand how the simulation is performing. This is recorder class; the name only suggests that it does the function of recording. This class is evoked as soon as the simulation begins, it records every state of the simulation from specified start duration and end duration for each specified interval of time. This block helps us extract the necessary parameters for examining the simulation results.

F. Verification and Validation

Verification and Validation is an important step in which we test the simulation using different test cases, where we think that there could be the possibility of getting inappropriate results.
By performing the simulation verification and validation we would be building a robust model that can handle critical situations similar to a real-world environment. This stage is dependent on the recorder class as the recorded parameters are checked to evaluate and interpret the results.

IV. Simulation Model

First of all, we will look at the parameters selected for different parts of the simulation study.

A. Multilane Mixed Simulation:

1) Car

Multilane Mixed Simulation- Car			
CRITICAL_TIME_TOLERANCE	4 s	Vmax	120/3.6 m/s
LANE_CHANGE_TIME	4 s	N	50
MIN_TIME_DIFF	1 s	IAT	10 s
MIN_SPEED_DIFF	4 m/s	Recorder	0-3000 s
CAR_LENGTH	5 m	Interval	1 s
FAR_AWAY_IN_FRONT	180 m	Lanes	2
FAR_AWAY_IN_BACK	70 m	Max Lane	5000 m
Speed Quantiles	As per RSA Graph	Lane Segment	1000 m

Figure 1: Parameters for Multilane Mixed Simulation- Car

2) Rigid Truck

Multilane Mixed Simulation- Rigid Truck			
CRITICAL_TIME_TOLERANCE	4 s	Vmax	120/3.6 m/s
LANE_CHANGE_TIME	8 s	N	50
MIN_TIME_DIFF	1 s	IAT	10 s
MIN_SPEED_DIFF	4 m/s	Recorder	0-3000 s
CAR_LENGTH	20 m	Interval	1 s
FAR_AWAY_IN_FRONT	250 m	Lanes	2
FAR_AWAY_IN_BACK	100 m	Max Lane	5000 m
Speed Quantiles	As per RSA Graph	Lane Segment	1000 m

Figure 2: Parameters for Multilane Mixed Simulation- Rigid Truck

B. Multilane Mixed Simulation for Multiple Vehicles

Multilane Mixed Simulation for Multiple Vehicles					
Vehicle Paramters\Vehicle Type	Family Car	Eelctric Car	Rigid Truck	Articulated Vehicle	Bus
CRITICAL_TIME_TOLERANCE	4 s	4 s	4 s	4 s	4 s
LANE_CHANGE_TIME	4s	3 s	7 s	10 s	6 s
MIN_TIME_DIFF	1 s	1 s	1 s	1 s	1 s
MIN_SPEED_DIFF	4 m/s	3 m/s	8 m/s	10 m/s	9 m/s
CAR_LENGTH	4m	4m	15 m	20 m	14 m
FAR_AWAY_IN_FRONT	200 m	150 m	250 m	270 m	230
FAR_AWAY_IN_BACK	80 m	60 m	100 m	120 m	90
Speed Quantiles	As per RSA Graph	As per RSA Graph	As per RSA Graph	As per RSA Graph	As per RSA Graph
Simulation Parameters	Vmax	N	IAT	Recorder	Interval
	120/3.6 m/s	400	30 s	0-1000 s	1 s
	Lanes	Max Lane	Lane Segment		
	2	3000 m	1000 m		

Figure 3: Multilane Mixed Simulation for Multiple Vehicles

C. Multilane Mixed Simulation for Multiple vehicles with Lane merging Behavior.

In this part of the project, all the vehicle specifications and simulation parameters are the same as in figure 3. There is only a minor change for implanting the lane merging for which we are creating 3 lanes of 2 km and 2 lanes of 1 km. Figure 4, gives the representation of the required lanes.

```
left Lane:  [2 2000m R:0]
centr Lane:  [0 2000m L:2 R:6]-[3 1000m R:7]
Right Lane: [6 2000m L:0]-[7 1000m L:3]
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Figure 4: Lane segments for merging behavior

Now we will look at different parts of the Simulation Model.

1) Model for Vehicles:

The model for vehicles contains multiple functions. __init__ function takes multiple parameters to initialize a vehicle that is self, env, rec, starting lane, starting position, time, location, velocity, acceleration, time and speed profiles. It keeps the state of the vehicle whether it is running, crashed, braking, changing lane, starting pos, starting lane. To check whether the car is crashed we use the logic that if the position of the car in front is less than the position of the car plus its length. To start the process of slow to fast lane change we check whether there is no car in front after that we check whether we are not self-braking and not in the state of lane changing process already. Then we check whether the speed of the car in front plus the minimum speed difference is greater than a self car. Also, we need to check if there is sufficient distance to change the lane. For that we use self-position plus, the addition of critical time tolerance and lane change time multiplied by self speed is greater than the car in front. Also, there shouldn't be a car on the immediate right side. After this, we check whether is there anyone in the right front and right back. If there are vehicles in the right front and right back we check that self car speed is not slower than the right-back car and self car speed is not faster than the car in the car in the right front. If and only if all these conditions are true then only lane changing process is called. A similar approach is used for coming back to the slow lane.

2) Model for Behavior of Human Drivers:

Different vehicle drivers can drive in a different style. Some might try to drive at a constant speed as possible. Some try to accelerate as possible if there is a car in front then reduce the speed. Some drivers accelerate up to a certain level and if they feel they accelerated more they reduce the speed and the cycle continues. To simulate this human behavior we create a random interval function that generates random time intervals using random normal variate or random expovariate. These time intervals are then used to increase or decrease the speed for that time interval. To generate speeds, we use the free motorway function that makes use of free speed and quantiles were taken from the RSA speed survey. Using this function, we can generate speed with the same distribution as drivers of different vehicles drive on the free-flowing motorway. The combination of these two functions inculcates human behavior in simulation.

3) Model for Autonomous or Computer-Assisted Driving:

The simulation model built in this study does not have any human intervention. The cars are created randomly depending on the specified value of the number of cars. The specifications of the cars are already available. Thus after vehicle creation, the vehicles operate on their own. The decisions of braking, emergency braking, lane change, acceleration are taken by the model itself. Even the Lane structure is specified before and lane segments are increased on their own up to specified maximum lane length.

4) Model for Motorway Section:

Motorways are a formation dual carriageway that allows the flow of fast traffic and there are few places for entering and leaving. These roads are specially built to reach longer distances in less time. Maximum allowed speeds for different vehicle type varies on Motorways. 120 km/hr is the maximum speed limit allowed on motorways. This maximum than any other type of road such as national roads, non-national roads, etc. To incorporate this behavior in the model we specify V_{max} value that assigns maximum allowed speed on the motorway. We can also create any kind of structure for the motorway. This can be achieved by specifying the maximum length of the motorway, segment block length. The model is flexible to widen or extend the lanes as per the requirements. We can also design motorways that can depict lane merging behavior.

5) Model for Traffic Generation:

The traffic generation process is simple in comparison to other parts of the simulation model. We need to Specify the value of N that is the number of vehicles to be considered for simulation. Depending on the value of n the traffic flow can be altered, higher the N, there would be more traffic on the road, lesser value means it having low traffic. For is used to form 1 to n specified to created that many calls for vehicle class and thereby further simulation begins. The important factor here is inter-arrival time because if all cars arrive at the same time there would be more cases of the crash at the beginning of the simulation. The model takes IAT as a parameter that is can be passed to either Normal, Uniform, or expovariate.

6) Data Collection:

Till now we looked at all the different aspects of the simulation process. These were essential to run the simulation but there is another aspect that is equally important for building simulation models is Data Collection. To assure that model is accurately handling each complex situation it is necessary to collect the relevant data. Recorder class contains the functionality of the collection data of the simulation. It contains basic start and stops recording functions. These functions are invoked when the recorder class is called. Then there is a record function that captures the surrounding environment, time, self-position, Velocity, Acceleration, Vehicle id, Lane Id, Old Lane Id and event. There is a plot function that allows us to plot Velocity, Acceleration, Time, Position. The data gets stored in the Data Frame. This Data Frame is returned when the Get_Data function is called.

V. RESULTS AND INTERPRETATION

A. *Multilane Mixed Simulation:*

Here we achieved similar results for both vehicle types. Throughput for Car is 95.94 Cars/Hour. The throughput of Rigid Truck is 95.84. Here we were expecting a significant difference in the throughput values of the Car and the Rigid Truck. Car having less length, lane changing time, distance in front and back achieved similar results as a rigid truck. Average traveling Time has a significant difference. For a rigid truck, the value is 48.48 s but for Car, it is 60.51 s. From below figure 5,6, we can interpret that for both the type of vehicles the graph is identical with slight variation. There is no presence of crash but there are instances where emergency brakes were applied that are represented by red dots.

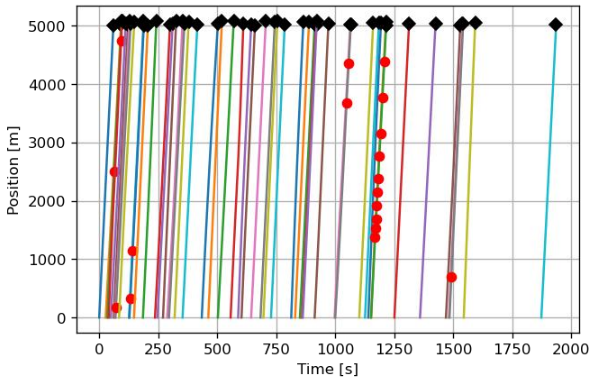

Figure 5: Position of the Cars with respect to time.

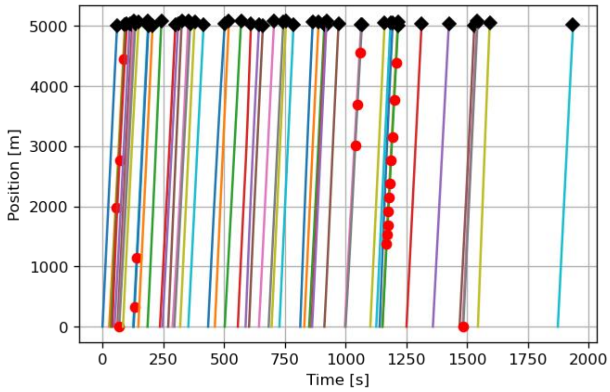

Figure 6: Position of the rigid trucks with respect to time.

B. *Multilane Mixed Simulation for Multiple Vehicles*

This simulation resulted in a throughput of 184 Cars/Hour. Optimal Average Travelling Time T_{opt} is 33 sec. The density of 5.51. Below Figure 7, represents the Position vs Time graph. It can be interpreted that most of the vehicles reached the endpoint without changing the lanes. 8 Vehicles had to change their lane. Only 2 vehicles applied braked at multiple instances.

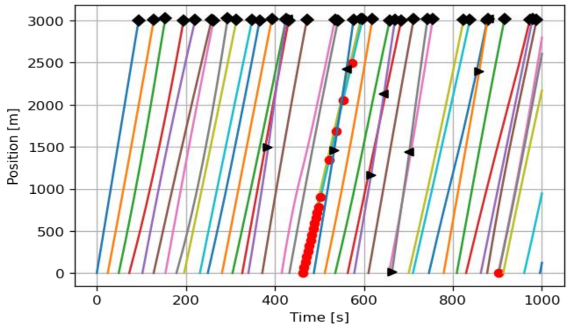

Figure 7: Position of the Multiple Types of vehicles with respect to time.

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left lane [0 1000m R:3]-[1 1000m R:4]-[2 1000m R:5]
right lane [3 1000m L:0]-[4 1000m L:1]-[5 1000m L:2]
t=  385.0s Overtaking v14 overtakes v13 at x=1,491.4m
t=  425.0s Overtaking v14 returns to slow lane at x=2,985.1m
t=  533.0s Overtaking v20 overtakes v18 at x=1,452.5m
t=  558.0s Overtaking v20 returns to slow lane at x=2,317.3m
t=  616.0s Overtaking v24 overtakes v23 at x=1,159.0m
t=  642.0s Overtaking v24 returns to slow lane at x=2,021.3m
t=  663.0s Overtaking v26 overtakes v27 at x=   11.5m
t=  698.0s Overtaking v26 returns to slow lane at x=1,284.3m
t=  859.0s Overtaking v31 overtakes v30 at x=2,392.8m
t=  877.0s Overtaking v31 returns to slow lane at x=2,987.3m
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Figure 8: Simulation Run of the Multiple Types of vehicles

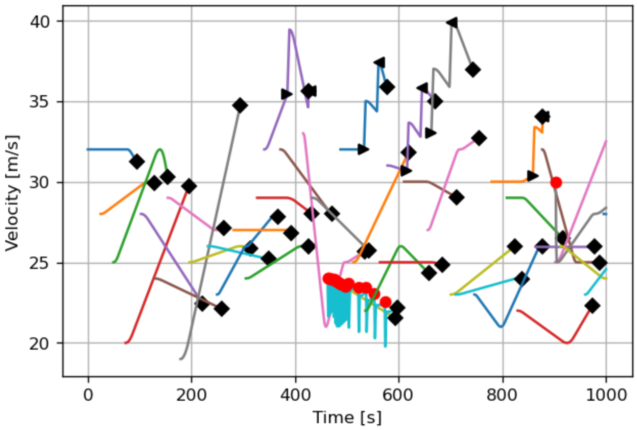

Figure 8: Velocity vs Time graph of Multiple Types of vehicles

From figure 8 we can see that the speed of the vehicle is getting randomly assigned.

C. *Multilane Mixed Simulation for Multiple vehicle Types with Lane merging Behavior.*

This is the final stage of the simulation, result of this part will help us understand how the model is adapting the lane merging behavior. The throughput achieved is 174 Cars/ hour. Average Optimal Travelling Time T_{opt} is 52.43 s. Density obtained is 3.32. The throughput is reduced than the second part of the study. T_{opt} reduced than the simulation study implemented without lane merging. The value of density is also reduced. These are the effects of lane merging. The important result is that there no instance of car crashes. The above figure [9] represents the graph of Position v/s Time.

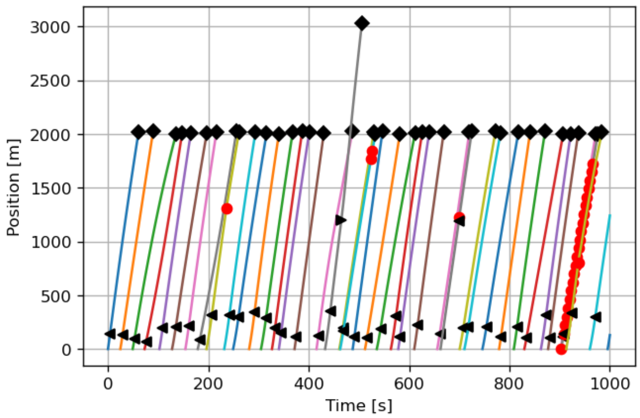

Figure 9: Position V/S Time graph for lane merging simulation.

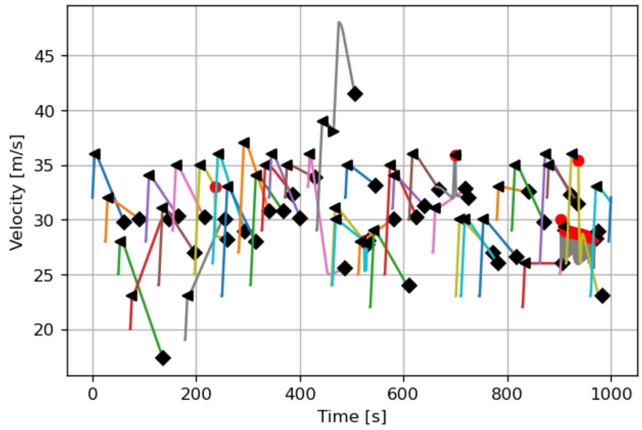

Figure 9: Velocity V/S Time graph for lane merging simulation

```
left Lane:  [2 2000m R:0]
centr Lane:  [0 2000m L:2 R:6]-[3 1000m R:7]
Right Lane: [6 2000m L:0]-[7 1000m L:3]
t=    0.0s Overtaking v0 returns to slow lane at x=    0.0m
t=   25.0s Overtaking v1 returns to slow lane at x=   10.4m
t=   50.0s Overtaking v2 returns to slow lane at x=   18.4m
t=   73.0s Overtaking v3 returns to slow lane at x=    1.9m
t=  103.0s Overtaking v4 returns to slow lane at x=   13.6m
t=  128.0s Overtaking v5 returns to slow lane at x=    7.3m
t=  155.0s Overtaking v6 returns to slow lane at x=   22.2m
t=  179.0s Overtaking v7 returns to slow lane at x=    2.9m
t=  197.0s Overtaking v8 returns to slow lane at x=   18.6m
t=  232.0s Overtaking v9 returns to slow lane at x=    8.9m
t=  250.0s Overtaking v10 returns to slow lane at x=   14.4m
t=  282.0s Overtaking v11 returns to slow lane at x=   19.1m
t=  305.0s Overtaking v12 returns to slow lane at x=    1.7m
t=  327.0s Overtaking v13 returns to slow lane at x=    6.4m
t=  341.0s Overtaking v14 returns to slow lane at x=   14.5m
t=  372.0s Overtaking v15 returns to slow lane at x=    8.1m
t=  416.0s Overtaking v16 returns to slow lane at x=   15.2m
t=  433.0s Overtaking v17 returns to slow lane at x=   11.0m
t=  461.0s Overtaking v19 returns to slow lane at x=    2.6m
t=  463.0s Overtaking v18 returns to slow lane at x=    6.8m
t=  465.0s Overtaking v17 overtakes v16 at x=1,201.7m
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Figure 10: Simulation Run of the Multiple Types of vehicles with lane merging.

VI. Conclusion

In this paper, a simulation study is implemented in three different stages to build the final model. From the first part of the study, we observed that the length of the vehicle, lane change time affect the results of the simulation. By simulating multiple types of vehicles with different speed distribution obtained higher throughput than the lane merging simulation. Thus, lane merging affects the results of the simulation study. Optimal traveling time also affects due to lane merging behavior, T_{opt} is reduced. Lane merging environment reduces the simulation density. As the value of vehicles in the simulation study increased the instances of crashes increased thus model needs to be improved so that it can handle a larger number of vehicles as well.

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