MODELLING HETEROGENEOUS TRAFFIC SYSTEMS: CONCEPTS AND METHODOLOGY

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Abstract

Models in general, enable understanding of concepts and systems with ease. They are highly useful in design, prediction, and evaluation of alternatives quickly, economically, and harmlessly. Different types of models are developed such as, physical, symbolic and mental models, depending upon the nature of the system. Experiments with models often lead to generation of new hypothesis and formalization of knowledge about systems. Road traffic flow being stochastic, they are too complex to be represented by a reasonable mathematical model. Hence, simulation technique is often used to model road traffic phenomena. Computer simulation models can play an important role in the analysis and assessment of the traffic-flow characteristics under heterogeneous traffic conditions such as the ones prevailing on Indian roads. An appropriate simulation framework to model heterogeneous traffic flow has been proposed here after description on certain conceptual aspects of modelling. The proposed methodology, when applied to field conditions, was found to be valid.

INTRODUCTION

A system is a collection of interacting elements or components that act together to achieve a common goal or toward the achievement of some logical end. The objective of many system studies is to predict how a system will perform before it is built. It facilitates to incorporate suitable modifications and appropriate changes in the system and its operating condition. Generally systems can be studied by two common methods. They are: (i) direct experimentation by building prototypes and (ii) doing experiments by building mathematical / logical models. The experimentation with the prototype or the real system is highly undesirable as they are expensive, impractical, risky and time consuming. Consequently, system studies are generally conducted with a model of the system. The purpose of systems study through modelling is to aid analysis, understanding, design, operation, prediction, or control of systems without actually constructing and operating the real thing.

SYSTEM MODELS

A model is a simplified representation of a system (or process or theory) intended to enhance our ability to understand, predict, and possibly control the behaviour of the system. The term model may mean different things to different people. The clay models for children, fashion models for an advertising agency, mathematical models for control engineers, and physical models for architects are some examples. The model representation of a system may take different forms. It may be mental, physical, or symbolic (Neelamkavil, 1987).

The quality and quantity of information contained in the above models may vary considerably, but they all have one major characteristic in common: they help us to evaluate the outcome of an action in a real-world situation without actually taking that action under real world condition. That is, one can evaluate alternatives without actually conducting live experiments.

Types of Models

Models can be classified in many ways and one of the classifications is to broadly divide them as physical and symbolic models shown in Fig.1. Physical models are representations of physical systems like electrical, mechanical, fluid, and thermal systems and they are made of tangible components. These models are described by measurable variables such as voltages, current, temperature, heat, length, weight, pressure, flow, force, velocity, etc. The construction of physical models could be expensive and time-consuming. Sometimes, it may be impractical and even impossible. Symbolic models are made of logical relationships, maps, graphs, pictures, words, etc. depending on the system to be modeled and the level of complexity involved in modeling the system.

Physical Models

Physical models can be further subdivided into static and dynamic models, are shown in Fig.2. The static models can divided into two distinct types as, (i) scale models and (ii) imitation models. Examples of scale models are: wax statues, models of cars, bridges, aircrafts, and ships. Examples of imitation models are: puppets, dolls, shop window models, molecular structure, cartoons, geological or political divisions in a map, etc. The dynamic models can also be divided into two categories as, (i) analogue models and (ii) prototypes. Examples of analogue models are: LCR (Inductance, Capacitance, Resistance) circuit to study car suspension system; mercury or alcohol to measure temperature; water flow to study traffic flow, blood flow, or money flow; rats and monkeys to test new medicines, etc. Examples of prototypes are: LCR circuit to study electrical oscillations, mass, spring, and damper assembly to test car suspension system; prototypes of chemical reactors; experimental management information system; functional railway engine, etc.

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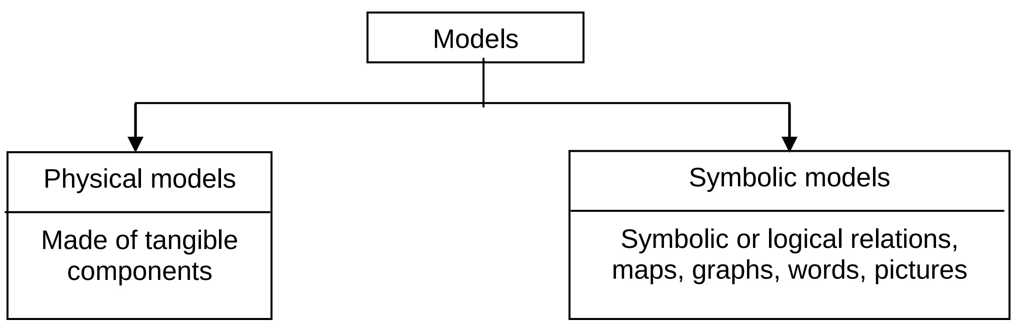


Fig. 1 Types of Models

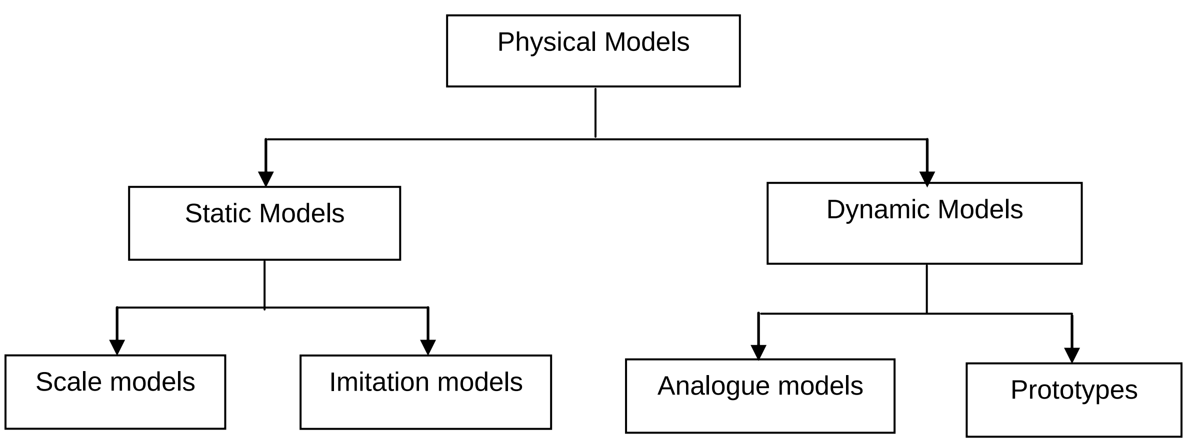


Fig. 2 Physical Models

Symbolic Models

Symbolic models are built easily and economically compared to physical models. The symbolic models can be broadly divided into two types as, (i) Mathematical models and (ii) Non-mathematical models. The classification system of symbolic models is shown in Fig.3.

Mathematical models

A mathematical model is a set of mathematical and logical relations between various system elements. A theory expressed in mathematical form is a mathematical model. Unquantifiable elements like attitudes, values, etc., cannot be included in mathematical models. The data derived from social and behavioural sciences tend to be qualitative rather than quantitative. Mathematical models expedite analysis; they are unambiguous and less expensive in evaluating alternatives. Some analytic models are mathematically interactable, and such models are expressed in terms of their approximate numerical equivalents which form the core of simulation models. The dynamic models are generally described by differential of difference equations, while algebraic equations characterize static mathematical models (Paul Brately et.al. 1987).

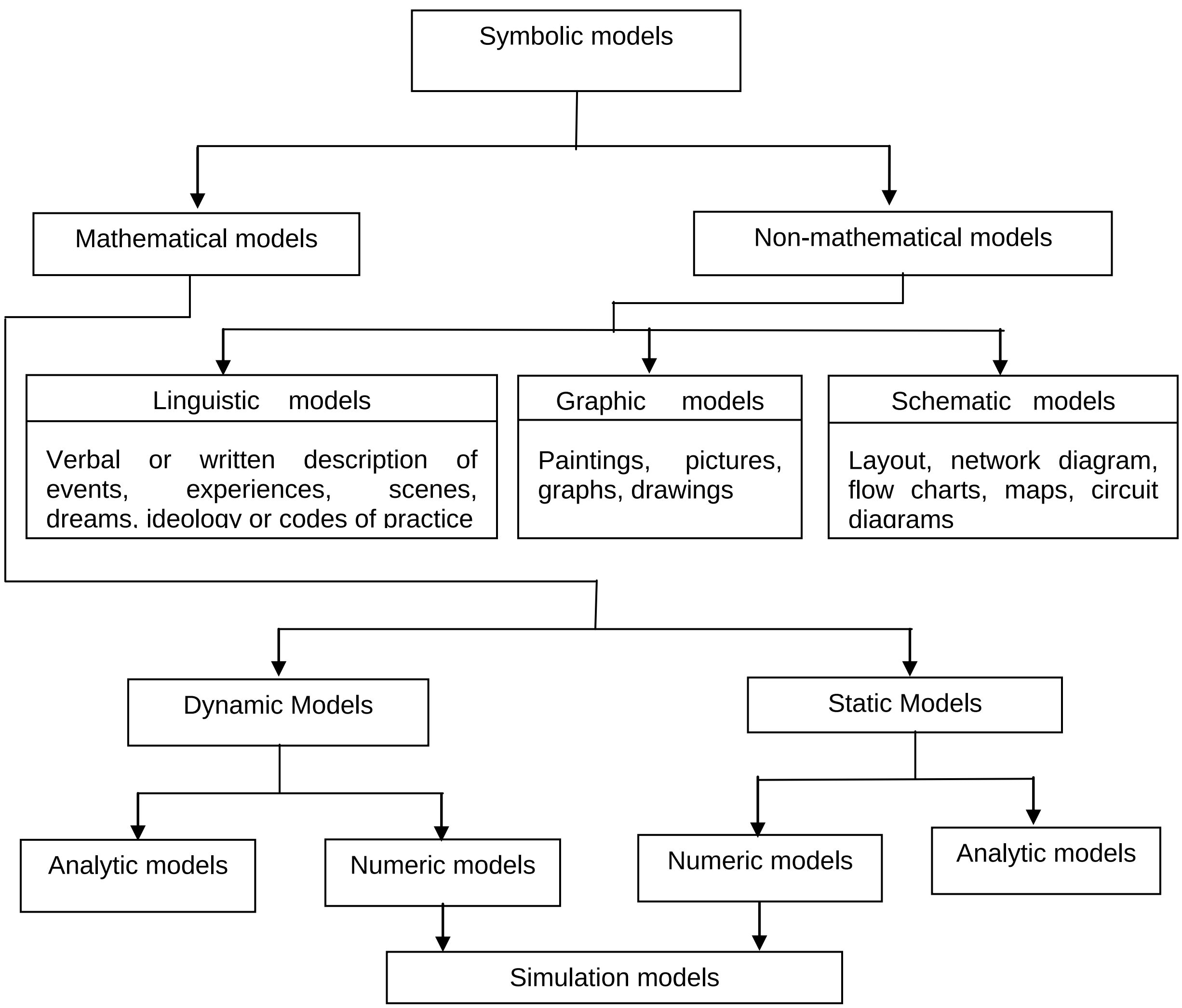


Fig. 3 Symbolic Models

SIMULATION

Simulation emerged as an identifiable numerical problem-solving technique during the World War II when the so-called Monte Carlo methods were successfully used by John Von Newmann and Stanislaw Valm of Los Alamos Scientific laboratory for solving neutron diffusion problems. Simulation does not necessarily involve computers. But availability of these devices has been the impetus to extend the application of simulation to many new areas. This process began with the development of analog computers, which were primarily applied to engineering design problems involving continuous models. Later the development of digital computers led to increased use of simulation in the areas of business and economics where discrete models wee prevalent. As digital computing has decreased in cost and become more available, it has become the dominant mode for the simulation of both discrete and continuous events (Gordon, 2001). These factors have led to the increasing use of computer simulation in almost all disciplines of study. With the current advances in digital computer technology, indications are that this trend will continue.

The simulation approach can be used to study almost any problem. However, it is a reasonable approach only under certain conditions. It requires that a model be constructed that represents system behaviour in terms of mathematical and logical relationships between variables. This model must adequately represent the primary effects which relate to the problem being studied. Until such a model is available, simulation can not be used. After a computer model of the system is available, simulation is used to investigate the performance of the system. Each simulation run is essentially an experiment of the system. The advantage of simulation is that these experiments can be completely controlled and observed (Banks et al. 2002).

TRAFFIC SIMULATION

Computer simulation models can play a major role in the analysis and assessment of the highway transportation system and its components (Roess et al. 1987). Often they incorporate the other analytical techniques, such as demand-supply analysis, capacity analysis, traffic stream models, car-following theory, shock wave analysis, and queuing analysis, into a framework for simulating complex components or systems of interactive components. These components may be individual signalised or unsignalised intersections, residential or central business district dense networks, linear or network signal systems, linear or corridor freeway systems, or rural two-lane or multilane highways systems (May,1990). Computer simulation model applications are not limited to highway transportation systems but have been used in all forms of transportation, such as bus systems, transit rail system, air transport system, waterway systems and elevator systems. In fact, computer simulation model techniques have no limits other than the creativity and resources of the developer and have been used in many fields outside of transportation.

In performing the simulation of a system, a normal sequence of events has evolved. It should be emphasized that the steps are neither sacred nor chronological. These steps indicate phases to be covered in an approximate order (Drew, 1968).

1. Definition of the problem specifically, in familiar terms and symbols with placement of the necessary limitations.
2. Formulation of the model, including the statement of assumptions, choice of criteria for optimization, and the selection of the operational procedure or rules of the road.
3. Construction of the block diagram, establishing the functional relationship between the components of the system to be simulated.
4. Determination of the inputs of the simulation program
5. Preparation of the computer simulation program'
6. Conducting experimental runs of the simulated system including experimental design to determine the number of runs and the parameter values to be used and to establish confidence limits
7. Evaluation and testing of the simulated system simulation

The most important step in a computer simulation of a traffic system is the formulation of the model. The computer is important in that it makes solution of the model practical, and the programming merely represents the means of communication between the investigator and the computer. However it must always be recommended that neither the simulation model nor the computer program represents an end in itself but is merely a means to solving a complex problem regarding the operation of an existing traffic system or the design of a future one.

The first important aspect in the formulation of the model is simplifying assumptions. The second aspect is the establishing the basic rules by which the design or operational improvement to be simulated can be measured. This is best accomplished by formulating the simulation model in such a way that the figures of merit are expressed as functions of the variables of the system being studied. Several such measures of effectiveness worthy of consideration are (1) travel time and speed –their averages, variances and distributions; (2) percentage of vehicles required to travel at some arbitrary fraction of their desired speed (3) acceleration noise in the analysis system (4) number of lane changes per vehicle per second (5) average platoon length and (6) the level of service as described.

Inherent to the formulation of the model are the determination of the significant input and output variables. Inputs may be divided into four categories: geometrics, traffic characteristics, driver policy, and vehicle performance. Important geometric variables are curvature, grade, number of lanes, sight distance, etc. The three fundamental characteristics of traffic movement –speed, volume and density, define the operational requirements of the traffic stream. The speed of a maneuvering vehicle has a significant effect on the particular maneuver- crossing, merging, weaving or lane changing. On the one hand, the size of gap required for the maneuver varies directly with the relative speed between the maneuvering vehicle and the stream across which, in to which or through which it desires to maneuver.

The transverse distribution and longitudinal distribution of vehicles on the simulated system may be described in terms of either volume or density. The longitudinal placement of vehicle in the traffic stream affects the driver choice of speed. The principal characteristics of traffic concern the abilities, requirements, and performance of the driver and vehicle, which together form the discrete unit of the simulation model. The objectives of the driver must be incorporated into the model. It may be to minimize his delay or maximize his safety. To complicate things, a driver's policy may not be consistent with the capabilities of his vehicle. A vehicle which gets trapped behind a slow moving vehicle is forced to reduce its speed. When a passing opportunity presents itself, the accelerating potential of the vehicle become yet another significant input to the model. The power of simulation as a tool for the study of traffic flow lies in the ability to include the effect of the random nature of traffic. We have a number of variables -some associated with the characteristics of the roadway, some with the characteristics of the driver, and some with the characteristics of the vehicle, is very large for most traffic systems (Wohl, 1967). These variables are expressed as frequency distributions and input into the simulation model.

MODELLING TRAFFIC FLOW

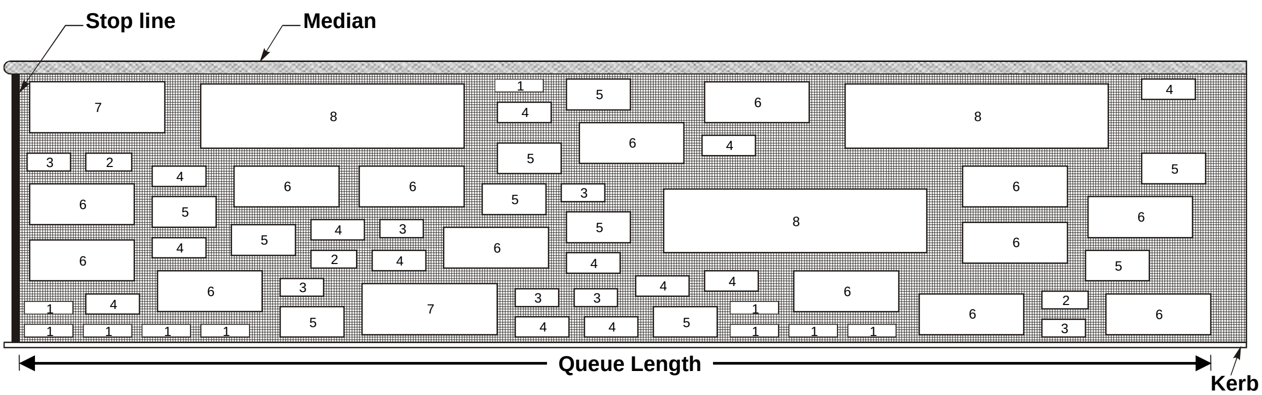
The traffic stream characteristics in terms of rate of flow, speed, delay etc,. are governed by the two elements, which are vehicle and the driver. As for vehicle factors, they may be subdivided into (a) dimensional aspects: width, height, length, weight, etc; and (b) mechanical performance aspects: braking power, turning capability, etc. Dimensional aspects directly affect the roadway design, the quality of traffic movement, and both vehicle and roadway cost. Mechanical features are important in two major respects such as setting limits for performance capabilities and determining the vehicle weight and equipment power requirements.

When the characteristics of vehicles constituting the traffic, fall over a short range, the traffic becomes homogeneous. The road traffic of developed countries comprises mostly cars with a small percentage of buses and trucks. Thus, the traffic on the roads of developed countries, are homogeneous in nature. The homogeneity facilitates maintenance of lane discipline for traffic streams, and queue discipline while the vehicles wait at traffic signals. Because of the inherent lane and queue discipline of homogeneous traffic, modelling homogeneous traffic using simulation technique has become relatively simple and straight forward.

The traffic scenario in developing countries like India is altogether different from that of in developed countries. Traffic in India comprises of vehicles with wide ranging static and dynamic characteristics such as acceleration, deceleration and turning capabilities. These traffic consists, on one hand, of slow moving vehicles like bicycles, cycle rickshaws and animal drawn vehicles; and on the other hand, fast moving vehicles like cars, vans, motorcycles, auto rickshaws and buses. The said vehicular mix has made the traffic highly heterogeneous and it has become extremely difficult to impose lane discipline and the vehicles use any part of the carriageway. As a result, the movement of fast moving vehicles is hindered by the presence of a slow moving vehicle. These conditions are prevalent in many other countries of the developing world and need a different treatment for analysis. The wide variety of vehicles and the disparity in their size and speed create a number of problems in traffic operations. Vehicles do not respect the lane markings and tend to utilize every possible lateral and longitudinal gap.

MODELLING HETEROGENEOUS TRAFFIC

Due to the complex characteristics of heterogeneous traffic, simulation procedure adopted for homogeneous traffic conditions cannot be applied to model heterogeneous traffic stream. However, due to the growing use of automobiles and its many externalities, the analysis of mixed traffic has always attracted the attention of researchers from all over the world. The studies on this aspect, reported so far, however, have not bear comprehensive enough to simulate heterogeneous traffic flow to match with the field observed traffic flow characteristics. An appropriate methodology to simulate heterogeneous traffic flow more accurately is suggested here. As per the methodology, the entire road space is considered as single unit. The road space will be considered to be a surface made of small imaginary squares (cells of convenient size); thus transforming the entire space into a matrix. The vehicles will be represented with dimensions (including the lateral and longitudinal clearances) as rectangular blocks occupying a specified number of cells whose co-ordinates will be defined before hand (Fig.5). This technique will facilitate identification of the type and location of vehicles on the road stretch at any instant of time during the simulation process (Arasan and Kashani, 2003).



1.Bicycles, 2. Mopeds, 3. Scooters, 4. Motorcycles, 5. Autorickshaws, 6. Cars, 7. Light Commercial Vehicles, and 8. Heavy Vehicles

Fig. 5 Representation of Vehicles of Heterogeneous Traffic on Road Space for SImulation

For the purpose of simulation, the time scan procedure was adopted. The scan interval chosen for the simulation is one second. The arrival of vehicles on the road stretch will be checked for every second and the arrived vehicles will be put on to entry point of the study stretch of the road on first-cum-first-serve basis. The vehicles then, will be placed on the matrix of the road surface to occupy logical positions, as rectangular blocks (in plan) starting from left side of the carriageway. The movement of the rectangular blocks on the imaginary matrix will simulate the movement of the vehicles on the carriageway. The proposed simulation process, which is intended to model traffic flow through signalised intersections basically, consists of the following three steps:

1. Vehicle generation; 2.Vehicle accumulation; and 3. Vehicle dissipation.

The flow chart shown in Fig.6 depicts the major logical steps involved in the over all simulation process involving the three steps.

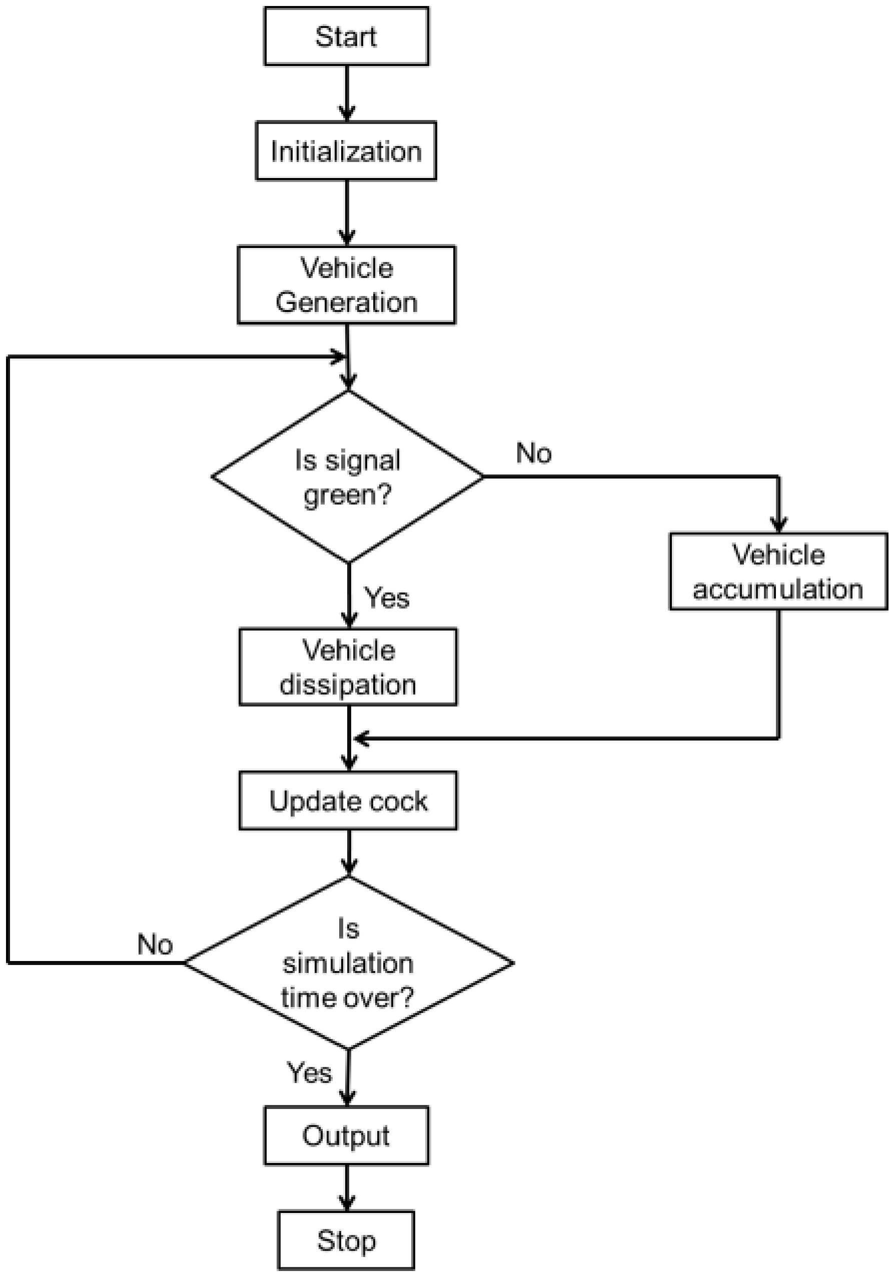


Fig. 6 Traffic-Simulation Framework

The computer program code to simulate the heterogeneous traffic flow through signalised intersections was written in C++ programming language. The program consisted of three major modules corresponding to the three major steps of the simulation process, namely, vehicle generation, vehicle accumulation and vehicle dissipation.

Vehicle Generation

In simulation experiments, it is often necessary to deal simultaneously with several random variables, which are independent. For example, in the generation of traffic streams, the inter-arrival time of vehicles follow different distributions, while the speed of the each vehicles follow another distribution. The two components related to vehicle generation are:
(i) Generation of vehicle arrivals, and (ii) Generation of vehicle speed.

Vehicle arrivals

As vehicle arrivals at an intersection is random, the random deviates for inter arrival times are generated by using negative exponential distribution, as time is a continuous function. Thus, the equation for desired random deviate becomes,

Inter-arrival time = -ln (random number)/ average flow rate

The corresponding mathematical form is given by

$$t = -\left(\frac{1}{\lambda}\right)\ln R_1 \quad \text{------(1)}$$

where, t is the inter-arrival time in seconds, λ is the mean arrival rate in veh/sec, and R_1 is the uniform random number.

Function rangen (0,1) is used to generate the uniform random number, where rand ( ) is the library function of C++ which returns huge random numbers. However, the random number 'a' generated above is a huge integer value. To convert this into a real value between 0 & 1 , a seed value, k is taken as (2^{15}-1). The random number a, is then divided by the seed of value k, which gives random numbers between 0 and 1. The generated random number is converted into negative exponential random number using inverse transformation method. Equation (1) tells us that in order to generate a negative exponential random deviates, one simply takes negative logarithm of a generated pseudo-random fraction. Random deviates generated above are compared with the cumulative probabilities or proportions of vehicle types. Using the cumulative probability of occurrence, of the vehicle types can be identified. For example, if the random deviate lies in a particular range, say, the range of car, then, the vehicle arrived is identified as car. Similarly all the vehicles are identified. The different types of vehicles grouped based on their static and dynamic characteristics, for the purpose of simulation, are as shown in Table1.

Table.1 Observed Vehicular Dimensions and Related Characteristics

Vehicle type	Vehicle Type	Overall Dimension (m)		Minimum Clear Space (m)*	
		Length	Breadth	Along Length	Along Breadth
1	Bicycle	1.9	0.5	0.1	0.1
2	Tricycle	2.5	1.3	0.1	0.1
3	MTW	1.8	0.6	0.2	0.2
4	Auto-Rickshaw	2.6	1.4	0.3	0.2
5	Car, Jeep, Van	4.2	1.7	0.5	0.3
6	LCV	5.0	1.9	0.6	0.3
7	Bus/ Truck	10.3	2.5	0.8	0.4

MTW – Motorised Two Wheeler; LCV – Light Commercial Vehicle; * space on each of the four sides of vehicle body which is used to calculate the longitudinal and lateral gaps between vehicles at zero speed condition.

Vehicle speed

While simulating the traffic flow, it is required to assign speeds to different vehicle types. In the simulation process, the vehicles will not be allowed to exceed their assigned free mean speed or desired speed. Speeds are generated using normal distributions and assigned to the each vehicle type. Box-muller transformation method is used to generate normal deviates s, by using the following equation

$$s = (2\log r_1)^{1/2}\cos(2\pi r_2) \quad \text{------(2)}$$

where r_1 and r_2 are random numbers and s is the random deviate.

Vehicle Accumulation

Vehicles generated as per the simulation-model framework, arrive at the approach road, and start accumulating on the road whenever the signal phase is red. As entire road space is divided into small cells, vehicles arriving successively will accumulate after checking for the availability of free road space from the stop line. Logic in the accumulation process is that vehicles try to occupy a position as closer to the stop line as possible. The vehicles are placed on the road space to occupy logical positions starting from left side of the carriageway.

As soon as certain road space is occupied by a vehicle, the imaginary rectangular block of breadth and length equal to the vehicle breadth and vehicle length including lateral and longitudinal clearances respectively, are filled by that particular vehicle number. Thus, vehicles arriving successively will have a clear idea about the already occupied road space.

Vehicle Dissipation

As soon as a signal phase changes from red to green, vehicles waiting at the atop line will start dissipating after the elapse of the reaction time of about 2 sec. Initially, the current speed of all the accumulated vehicles is zero. The positions of all the vehicles, waiting in the system, are updated for each scan interval i.e., one second. The distance a vehicle can travel, and the current speed, for each vehicle at the end of scan interval are calculated by the following equations

$$s = ut + \frac{1}{2}at^2 \qquad \text{------------(3)}$$

$$v = u + at \qquad \text{------------(4)}$$

where s – distance a vehicle can travel in time ‘t’ in ‘m’ ; u- initial speed in m/sec; v- final speed in m/sec t- scan interval in sec; and a- acceleration in m/sec^2

At the end of each scan interval, current speed of each vehicle is compared with the maximum allowable speed of that vehicle. If it exceeds maximum speed, current speed is assigned as maximum speed of that vehicle. Finally, the simulation output will provide information, for each type of vehicle, like vehicle position i.e, its x and y co-ordinates, current sped and acceleration, etc at any instant of time, and on any stretch of the road.

Model Verification and Validation

Verification is a procedure to ensure that the model is built according to specifications and to eliminate errors in the structure, algorithm, and computer implementation of the model. Verification pertains to the computer program prepared for the simulation model, and is intended to check whether the computer program performs properly. With complex models it is difficult, if not impossible, to translate a model successfully in its entirety without a good deal of debugging. If the input parameters and logical structure of the model are correctly represented in the computer, verification has been completed. For the most part, common sense is used in completing this step. It is one of the most important and difficult tasks facing a model developer.

The validation problem arises because various approximations to reality are made in creating the model. Validation is the determination that a model is an accurate representation of the real system. Validation is usually achieved through the calibration of the model, an iterative process of comparing the model to actual system behaviour and using the discrepancies between the two, and the insights gained, to improve the model. This process is repeated until model accuracy is judged acceptable. The goal of the validation process is two fold: (1) to produce a model that represents true system behaviour closely enough for the model to be used as a substitute for the actual system for the purpose of experimenting with the system; and (2) to increase to an acceptable level the credibility of the model, so that the model will be used by managers and other decision makers.

The model, after verification, was validated using field observed data. For the purpose of validation, the arrival, accumulation and dissipation of straight on vehicles, on an approach of a signalised intersection (the north approach on Kamarajar Raod of the junction of Radhakrishnan Road with Kamarajar Road in Chennai City) were simulated using the model. Then the field observed and simulated flow characteristics of the particular traffic stream were compared to determine the level of matching. Comparison of observed and simulated queue characteristics is shown in Table.2. It can be seen that the error varies from -5.72 to +1.96 percent which is normally acceptable in the case of simulation experiment.

Table 2. Results of Model Validation Based on Queue Characteristics

Description	Value		Percentage Error
	Observed	Simulated	
Average Number of Vehicles in Queue	31.48	30.75	-2.37
Average Queue Length (m)	54.52	55.59	1.96
Average Queue Clearance Time (s)	25.02	23.59	-5.72
Average Number of Vehicles Passing the Study Section Over a Period of 4000 s	2469	2446	-0.93

CONCLUSIONS

Problem solving by modelling and simulation is an iterative process involving system analysis; formulation of hypothesis; formulation of mathematical / logical models; identification of solution strategy; numerical solution of equations; simplification and validation of models; computer adaptation of models; computer programming; organization of computer runs; documentation of all the details; and collection, analysis, and interpretation of results. Modelling traffic system using computer simulation assists in the decision making, to use the highway infrastructure effectively, especially with mixed traffic conditions. The successful application and validation of the proposed simulation methodology for modelling heterogeneous traffic flow indicates that the methodology has good potential for modelling complex mixed traffic systems.

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