Concentration of Heterogeneous Road Traffic

Thamizh Arasan Venkatachalam and Dhivya Gnanavelu
Department of Civil Engineering
Indian Institute of Technology Madras
India

1. Introduction

Traffic flow theories seek to describe in a precise mathematical way the interactions between the vehicles and their operators and the infrastructure. As such, these theories are an indispensable construct for all models and tools that are being used in the design and operation of roads. The scientific study of traffic flow had its beginnings in the 1930's with the study of models relating volume and speed (Greenshields, 1935), application of probability theory to the description of road traffic (Adams 1936) and the investigation of performance of traffic at intersections (Greenshields et al., 1947). After World War II, with the tremendous increase in use of automobiles and the expansion of the highway system, there was also a surge in the study of traffic characteristics and the development of traffic flow theories. The field of traffic flow theory and transportation while better understood and more easily characterised through advanced computation technology, are just as important today as they were in the early days. The fundamentals of traffic flow and their characteristics have become important and form the foundation for all the theories, techniques and procedures that are being applied in the design, operation, and development of road transportation systems. Traffic Flow is characterised by the movement of individual drivers and vehicles between two points and the interactions they make with one another. Unfortunately, studying traffic flow characteristics is difficult because driver behavior is something that cannot be predicted with one-hundred percent certainty. Fortunately, however, drivers tend to behave within a reasonably consistent range and, thus, traffic streams tend to have some reasonable consistency and can be roughly represented mathematically. The fundamental characteristics of traffic flow are flow, speed and concentration. These characteristics can be observed and studied at the microscopic and macroscopic levels. Table 1 provides a framework for distinguishing these characteristics.

Traffic Characteristics	Microscopic	Macroscopic
Flow	Time Headways	Flow Rates
Speed	Individual Speeds	Average Speeds
Concentration	Distance Headways	Density

Table 1. Framework for fundamental characteristics of traffic flow

This chapter is concerned with the macroscopic traffic flow characteristics and the associated analysis.

2. Traffic Flow Characteristics

2.1 Flow/Volume

Flow, the macroscopic traffic flow characteristic, is quantified directly through point measurements, and by definition, requires measurement over time. Thus, flow *(q)* also termed as volume, is defined as number of vehicles passing a point on a highway during stated period of time, which is given by,

$$q = N/T \tag{1}$$

where, N = Number of vehicles passing a point on the roadway in T;
T = Total observation period.

Flow rates are usually expressed in terms of vehicles per hour, although the actual measurement interval can be much less.

2.2 Speed

Measurement of the speed requires observation over both time and space. The distinction can be made between different ways of calculating the average speed of a set of vehicles. The average traffic stream speed can be computed in two different ways: a time-mean speed and a space-mean speed. The difference in speed computations is attributed to the fact that the space-mean speed reflects the average speed over a spatial section of roadway, while the time-mean speed reflects the average speed of the traffic stream passing a specific stationary point over a specified period of time.

2.2.1 Space Mean Speed

The average speed of a traffic stream computed as the length of roadway segment *(L)* divided by the total time required to travel the segment is the space mean speed. To calculate space mean speed, speeds of individual vehicles are first converted to individual travel time rates, then, an average travel time rate is calculated. Finally, using the value of average travel time rate, an average speed is calculated which is termed as space mean speed. It is given by,

$$u_s = \frac{L}{\frac{1}{N}\sum_{i=1}^{N} t_i}$$

Where t_i is the time for the vehicle i to cross the distance L, which is given by $t_i = L/u_i$, Hence,

$$u_s = \frac{L}{\frac{1}{N}\sum_{i=1}^{N} \frac{L}{u_i}} = \frac{L}{\frac{L}{N}\sum_{i=1}^{N} \frac{1}{u_i}}$$

$$u_s = \frac{1}{\frac{1}{N}\sum_{i=1}^{N}\frac{1}{u_i}} \tag{2}$$

where, u_i = speed of an individual vehicle i;
N = the number of vehicles passing a point during the selected time period.

2.2.2 Time Mean Speed

The average speed obtained by taking the arithmetic mean of the speed observations is termed the time-mean speed. Since individual speeds will be recorded for vehicles passing a particular point over a selected time period, time mean speed can be expressed as

$$u_t = \frac{1}{N}\sum_{i=1}^{N} u_i \tag{3}$$

where, u_i = speed of an individual vehicle i;
N = the number of vehicles passing a point during the selected time period.

All authors agree that for computations involving mean speeds to be theoretically correct, it is necessary to ensure that one has measured space mean speed, rather than time mean speed, since time-mean speeds do not provide reasonable travel time estimates unless the speed of the point sampled is representative of the speed of all other points along a roadway segment. Under congested conditions, it is important to distinguish between these two mean speeds. For freely flowing traffic, however, there will not be any significant difference between the two. When there is great variability of speeds, there will be considerable difference between the two.

2.3 Density

Traffic density, the macroscopic characteristic of traffic concentration, is defined as the number of vehicles occupying unit length of roadway at any instant of time and is given by,

$$k = \frac{N}{L} \tag{4}$$

where, L = length of the roadway;
N = the number of vehicles present over L at an instant of time.

2.4 Time-Space Diagram

Traffic engineers represent the location of a specific vehicle at a certain time with a time-space diagram. Figure 1 shows the trajectories of a set of five vehicles (numbered from 1 to 5), through time, as they move in one direction on a road. Certain characteristics, such as headway, speed, flow, density, etc. can be depicted using the diagram (Figure 1).
In the figure, the slope of time- space plot for each vehicle, *dx/dt* equals speed, *u*. The time difference between pairs of consecutive vehicles along the horizontal line is the headway

between those vehicles. For example, h_{t23} is the time headway between 2nd and 3rd vehicles in the traffic stream (t_3 minus t_2). The difference in position between consecutive vehicles along vertical line is the spacing (space headway) between vehicles. For example, h_{s23} is the spacing between 2nd and 3rd vehicles in the traffic stream (x_2 minus x_3). The number of vehicles that the observer would be able to count at a point A on the road over a period of observation T, namely flow, is equal to the number of vehicle trajectories the horizontal line AA intersects during the time period. The number of time-space plot that are intersected by the vertical line BB corresponds to the number of vehicles occupying the section of roadway at that instant of time, which is nothing but density *(k)*.

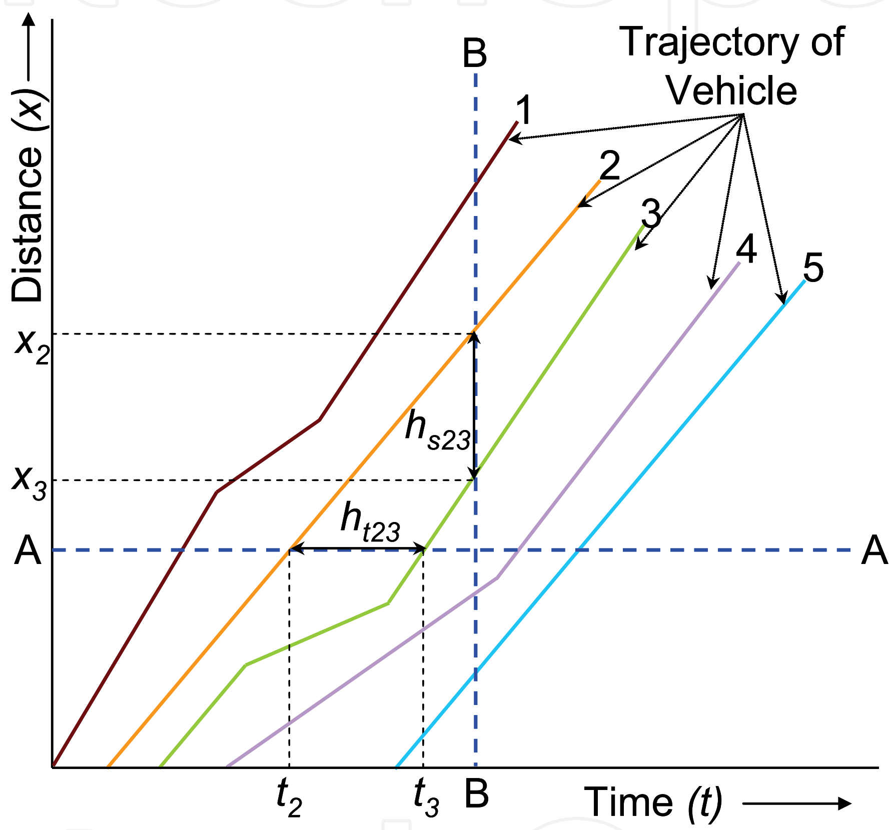


Fig. 1. Time-space diagram showing trajectories of vehicles over time and space

2.5 Fundamental Relations of Traffic Flow Characteristics

The relationship between the basic variables of traffic flow, namely speed *(u_s)*, flow *(q)*, and density *(k)* is called the fundamental relations of traffic flow characteristics and mathematically, it is expressed as,

$$q = ku_s \tag{5}$$

The relationships between the three basic characteristics, taken two at a time, are illustrated from Figure2 through 4. It may be noted that the nature of the relationships depicted in the figures are based on the assumption that the speed and density are linearly related (Greenshields model).

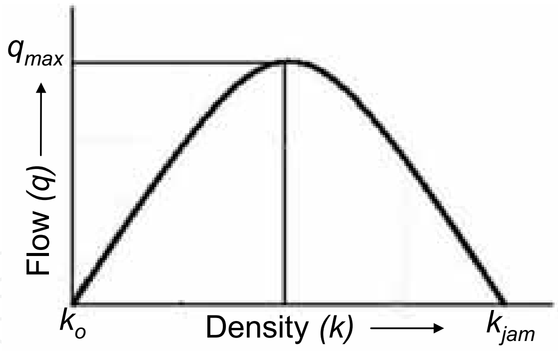


Fig. 2. Flow-Density Curve

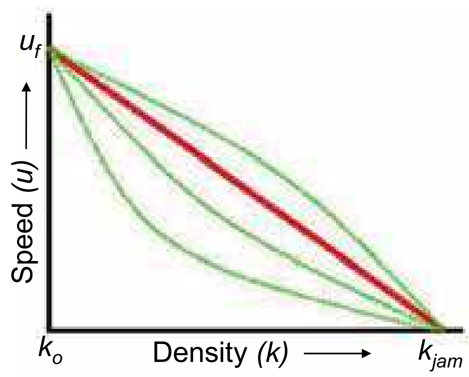


Fig. 3. Speed-Density Curve

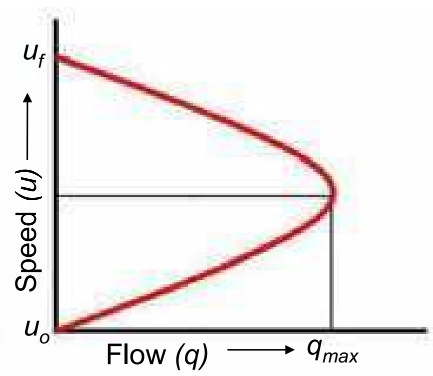


Fig. 4. Speed-Flow Curve

2.5.1 Flow-Density Relation

The flow and density vary with time and location. The graphical representation of the relation between density and the corresponding flow, on a given stretch of road, is referred to as the fundamental diagram of traffic flow (Figure 2). Some characteristics of an ideal flow-density relationship are listed below:

1. When density is zero, flow will also be zero, since there are no vehicles on the road.
2. When the number of vehicles gradually increases, the density as well as flow increases.
3. Increases in density beyond the point of maximum flow (q_{max}) results in reduction of flow.
4. When more and more vehicles are added, it reaches a saturation level where, vehicles can't move. This is referred to as the jam density or the maximum density (k_{jam}). At jam density, flow will be zero because the vehicles are not moving.
5. The relationship is normally represented by a parabolic curve

2.5.2 Speed-Density Relation

The simplest assumption is that the variation of speed with density is linear (Figure 3). Corresponding to the zero density, vehicles will be flowing with their desire speed, or free-flow speed (u_f). When the density is jam density, the speed of the vehicles becomes zero. It is also possible to have non-linear relationships between speed and density as shown by the dotted lines.

2.5.3 Speed-Flow Relation

The relationship between the speed and flow (Figure 4) can be postulated as follows. The flow is zero either because there are no vehicles or there are too many vehicles so that they cannot move. At maximum flow, the speed will be in between zero and free flow speed.

So far, the fundamentals of traffic flow and the necessity to study them in detail was briefly explained. Also, the characteristics of traffic flow such as flow, density and speed and the relationship between them were explained. Generally, motorists perceive lowering of the quality of service when the traffic concentration on the road increases. In other words, for a given roadway, the quality of flow, changes with the traffic concentration on the road. Thus, the measure 'concentration' provides a clear indication of both the level of service being provided to the users and the productive level of facility use. Hence, there is a need for in-depth understanding of traffic flow characteristics with specific reference to concentration. Accordingly, the following sections are focused on the in-depth study of traffic concentration.

3. Concentration

Concentration is a traffic measure which explains the extent of usage of road space by vehicles. It is a broader term encompassing both density and occupancy. The first is a measure of concentration over space; the second measures concentration over time of the same vehicle stream.

Traffic density, as mentioned earlier is the number of vehicles occupying unit length of roadway at any instant of time. Hence, traffic density can be measured only along a stretch of roadway. The length and width of roadway, usually considered for measurement of density are 1 km and one traffic lane, respectively. The existing Techniques include photographic and input-output counts. In photographic technique, the number of vehicles occupying a section of roadway is counted using the photograph taken aerially on the road section. In input-output counts technique the number of vehicles, crossing two reference points chosen on a section of roadway, are counted. The number of vehicles occupying a section of roadway between these two reference points is obtained by finding the difference between the numbers of vehicles counted at two reference points at any instant of time.

Due to difficulty in the field measurement, density needs to be calculated from speed and flow. Density can be calculated from field measured values of traffic volume and speed as

$$k = \frac{q}{u_s} \tag{6}$$

where, k = density in vehicles per lane per km;
q = flow rate in vehicles per hour;
u_s = space mean speed in km per hour.

Density, expressed as number of vehicles per unit length of roadway, is valid only under highly homogeneous traffic conditions, wherein the difference in individual vehicle speeds and vehicle dimensions are negligible. In practice, however, even under homogeneous traffic conditions, there are significant differences in the said two characteristics (speed and dimension) of vehicles. The measure, density, hence, becomes inapplicable for conditions with variations in the speed and dimensions of vehicles in the traffic stream. Hence, there is a need for development of an appropriate alternative measure to represent traffic concentration with potential for application to traffic conditions where there is significant difference in speed and dimension of vehicles.

Realizing the need for development of an appropriate measure to represent traffic concentration, several research attempts have been made on the subject matter in the past. First, an attempt was made to compute concentration based on the number and speeds of vehicles measured at a point (Greenshields, 1960) and this computed factor named, 'occupancy' was used as a surrogate for density. Then, as refinement of the concept, occupancy was defined as a non-dimensional variable which can be measured directly by the proportion of time during which a single point on a roadway is covered by all vehicles (Athol, 1965). It is calculated as,

$$Occupancy\ (\rho) = \frac{\sum t_i}{T} \tag{7}$$

where, t_i = time during which a single point on a roadway is covered by vehicle i;
T = the total observation period.

As can be seen from equation (7), occupancy is a non-dimensional variable. Since occupancy is a function of speed and length of a vehicle, it could consider the effect of varying vehicle lengths and speeds. Hence, occupancy can be used as a surrogate of density for measuring concentration of road traffic where there is significant difference in speed and dimension of vehicles.

Most traffic control systems that use a macroscopic density characteristic as the control variable can use the measured occupancy directly without converting to density (May, 1990). Hence occupancy can be considered as a logical substitute of density. It has been used as an indicator of establishing level of service criteria for freeways by developing a relationship between speed flow and occupancy (Lin et al., 1996).

Researchers also derived relationships between density and occupancy for homogeneous traffic conditions. Initially, a linear relationship was postulated assuming that all the sub-streams had constant vehicle length and constant speed (Athol, 1965), which is expressed as,

$$Occupancy,\ \rho = (l + d) \times k \tag{8}$$

where, k = density of traffic stream;
d = length of the detection zone;
l = length of the vehicle.

The difficulty in using equation (8) to estimate density is that the equation is valid only under ideal traffic condition wherein vehicles are of same length and maintain same speed.

4. Measurement of Occupancy

Based on the definition of occupancy (equation (7)), it can be inferred that vehicles are to be detected while passing a point or line across the roadway to get the required data for estimating occupancy. In practice, however, one is no longer dealing strictly with a point measurement, but with measurement along a short section of road using detectors. In other words, occupancy, based on practical consideration, is defined as the percentage of time the detection zone is occupied by the vehicles (May, 1990) and is given by,

$$\rho = \frac{\sum (t_i)_O}{T} \tag{9}$$

where, $(t_i)_O$ = time during which the detection zone on a roadway is covered by vehicle i and the subscript, o stands for occupancy;
T = the total observation period.

Since, the time during which a detection zone is covered by vehicles, is automatically recorded by detectors, occupancy can be easily measured in the field using detectors.
Occupancy measured using detectors depends on the length of the detection zone, each detector type has a differing zone of influence (detector length) and the length of the zone of influence is effectively added to the vehicle length to calculate occupancy. Hence, the measured occupancy may be different for different detection zones (detectors) even for the same roadway and traffic conditions, depending on the size and nature of the detectors. This implies that it is necessary to consider length of the detection zone (on which the presence of vehicle is detected) also in the formulation, in order to standardize the measurement of occupancy.

5. Occupancy of Heterogeneous Traffic

The afore mentioned concept of occupancy is specific to lane based traffic flow. The road traffic in countries like India is highly heterogeneous comprising vehicles of wide ranging static and dynamic characteristics as shown in Figure 5. The different types of vehicles present in the traffic on major urban roads in India can be broadly grouped into eight categories as follows: 1. Motorized two-wheelers, which include motor cycles, scooters and mopeds, 2. Motorized three-wheelers, which include Auto-rickshaws – three wheeled motorized transit vehicles to carry passengers and tempos – three wheeled motorized vehicles to carry small quantities of goods, 3.Cars including jeeps and small vans, 4. Light commercial vehicles comprising large passenger vans and small four wheeled goods vehicles, 5. Buses, 6. Trucks, 7. Bicycles and 8.Tricycles, which include Cycle-rickshaws-three wheeled pedal type transit vehicles to carry a maximum of two passengers and three wheeled pedal type vehicles to carry small quantity of goods over short distances. By virtue of their wide ranging characteristics, the vehicles do not follow traffic lane and occupy any lateral position over the width of roadway depending on the availability of road space at a given instant of time. Hence, it is nearly impossible to impose lane discipline under such conditions. To analyze such characteristics of the heterogeneous traffic, it becomes necessary to consider the whole of the width of road as single unit. Hence, when the occupancy concept is applied to heterogeneous traffic, it is necessary to consider the area (length and width) of the detection zone and the area of vehicles as the bases.

Fig. 5. The heterogeneous traffic on an Indian road

6. Area-Occupancy

Considering all the said issues related to occupancy, a modified concept of occupancy, named, 'Area-Occupancy', appropriate for heterogeneous traffic condition, is proposed here, which considers the horizontal projected area of the vehicle, without any restriction on the length of detection zone and width of road (treating the whole of the width of road as single unit, without consideration of traffic lanes), as the basis for measurement (Arasan & Dhivya, 2008). Accordingly, considering a stretch of road, area-occupancy is expressed as the proportion of time the set of observed vehicles occupy the detection zone on the chosen stretch of a roadway. Thus, area-occupancy can be expressed mathematically as follows;

$$AreaOccupancy, (\rho_A) = \frac{\sum_i a_i (t_i)_{AO}}{AT} \quad (10)$$

where, $(t_i)_{AO}$ = time during which the detection zone is occupied by vehicle i in s and the subscript, $_{AO}$ stands for area-occupancy;

a_i = area of vehicle i falling on the detection zone in m^2;

A = area of the whole of the road stretch (detection zone) in m^2;

T = total observation period in s.

6.1 Advantages of the concept of Area-Occupancy

The area-occupancy is not affected by the length of the detection zone since it considers the length of the detection zone in its formulation. Also, the effect of heterogeneity and lane less nature of the traffic is incorporated in the concept of area-occupancy by consider the area (length and width) of the vehicle in its formulation. Hence, the concept of area-occupancy is valid to measure, accurately, the extent of usage of road space by vehicles. Thus, area-occupancy, rather than occupancy, can be used as indicator of road traffic concentration at any flow level because of its ability to accurately replicate the extent of usage of the road. It may be noted that the area-occupancy concept can be applied to any traffic condition, from highly homogeneous to highly heterogeneous, and to any length of the detection zone.

6.2 Measurement of Area-Occupancy

In the case of measurement of area-occupancy using vehicle-detection loops, according to the definition of time $(t_i)_{AO}$ in equation (10), it is the time interval from the instant the front of a vehicle enters the detection zone to the instant the rear of the vehicle leaves the detection zone.

As the area-occupancy concept is applicable for any length of detection zone, two cases are possible in the measurement of area-occupancy. One is the measurement of area-occupancy on the detection zone whose length is less than the vehicle length (Figure 6(a)) and the other is the measurement of area-occupancy on a detection zone of length more than the vehicle length (Figure 6(b)). The time $(t_i)_{AO}$ of a vehicle can be split into three different time components, namely, t_1, t_2 and t_3, where t_1 is the time taken for the projected area of vehicle to fully cover the detection zone (when the length of the detection zone is less than the vehicle length) / fully fall on the detection zone (when the length of the detection zone is more than the vehicle length), t_2 is the time interval, after t_1, during which the horizontal projected area of the vehicle falling on the detection zone remains unchanged and t_3 is the time taken by the vehicle, after t_2, to clear off the detection zone. Thus, the distance traveled by a vehicle during the time $t_1+t_2+t_3$ is $(l+d)$, where, l is the length of the vehicle and d is the length of the detection zone.

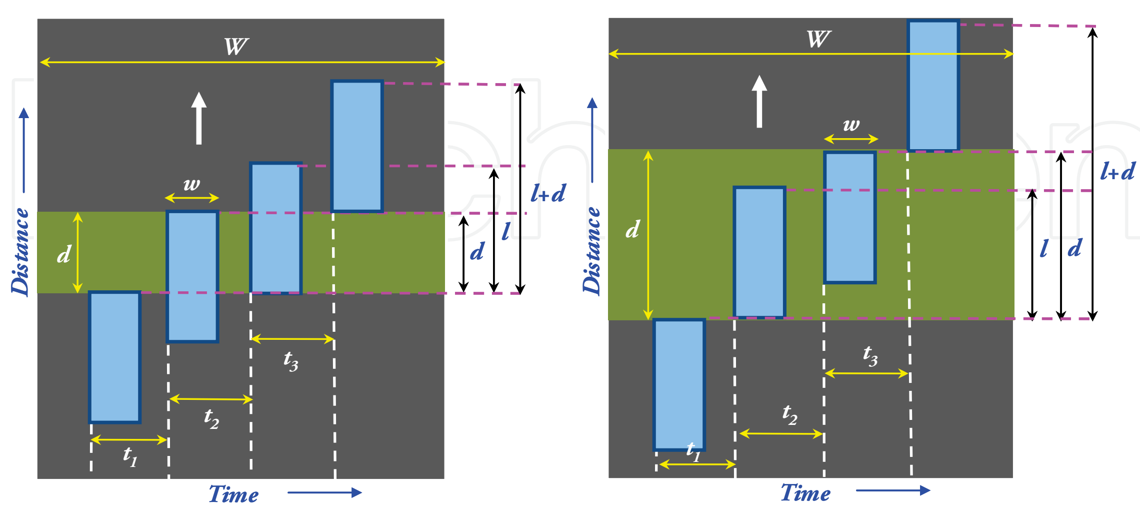


Fig.6. Principle involved in the measurement of area-occupancy

There are some issues involved in the measurement of time component $(t_i)_{AO}$ of area-occupancy and these are explained using the trajectories of vehicles depicted in Figure 7(a) and 7(b). It can be seen that during the time t_2, the whole length of the detection zone will be occupied by the vehicle in the case where the length of the detection zone *(d)* is less than the vehicle length *(l)* (B in Figure 7(a)) or the whole length of the vehicle will be occupying the detection zone where the length of the detection zone is more than the vehicle length (B in Fig 7(b)). Hence, during the time t_2, the area of the detection zone occupied by the vehicle, at any instant of time, will be constant, which is equal to a_i = length of the detection zone multiplied by the width of the vehicle (when $(d < l)$) or length of the vehicle multiplied by the width of the vehicle (when $(d > l)$). On the other hand, during the times t_1 and t_3, the detection zone is occupied by the vehicle only partially. Hence, in the time durations t_1 and t_3, the area of the detection zone occupied by the vehicle progressively varies and it is always less than a_i. Due to this, during the times t_1 and t_3, in the formulation of area-occupancy, the component, $a_i(t_i)_{AO}$ (with t_i being considered to be t_1+t_2+t_3) will overestimate the occupancy of the vehicle. That is, the occupancy will be estimated as (A+B+C+D+E) while the actual occupancy value is only (A+B+C).
Assuming the speed maintained by a vehicle to be constant on the detection zone, the contribution of this vehicle, to occupancy, during the time interval t_1 (A in Figure 7(a) and 7(b)) will be equal to the occupancy-contribution during the time interval t_3 (C in Figure 7(a) and 7(b)). Hence, the problem of over estimation of occupancy value can be solved if the time interval $(t_i)_{AO}$ is considered as either (t_1+t_2) or (t_2+t_3) as (A+B+C) is equal to either B+(A+D) or B+(C+E). Also, the area a_i in equation (10) is equal to the length of the detection zone multiplied by the width of the vehicle (when $(d < l)$) or equal to the horizontal projected area of the vehicle (when $(d > l)$).

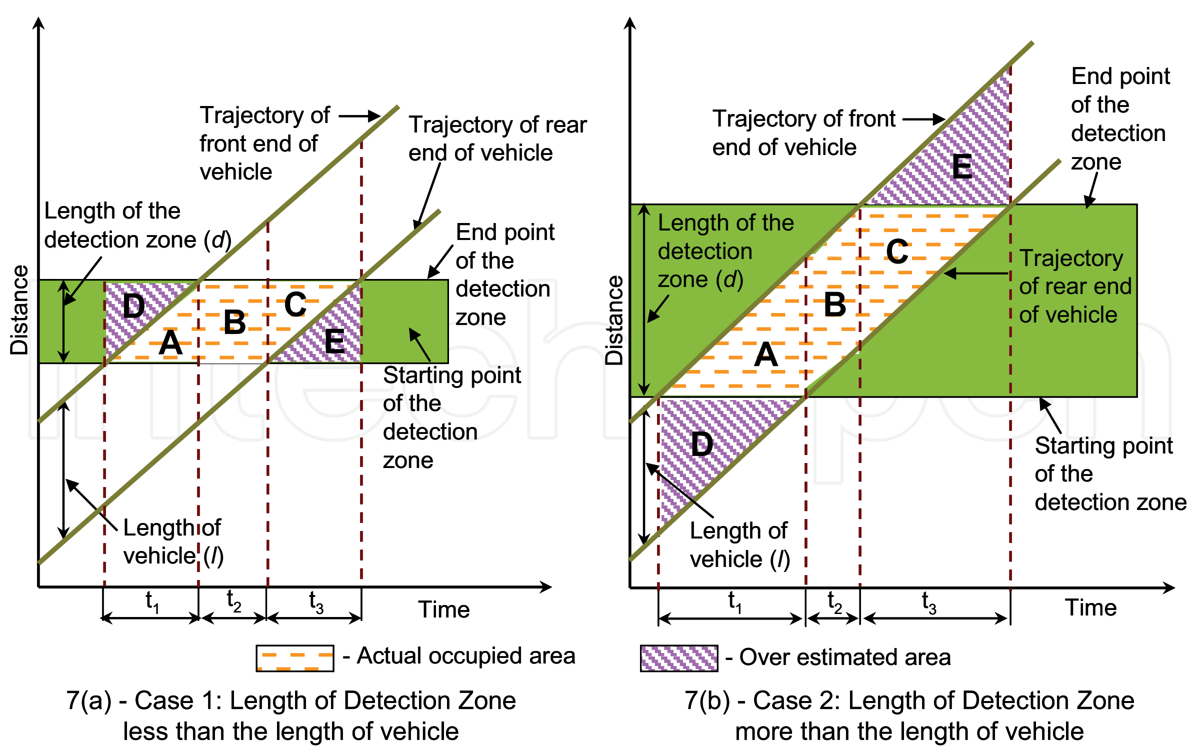


Fig. 7. Principle of measurement of time component of area-occupancy

The applicability of the area-occupancy concept to real world condition can be verified by estimating the area-occupancy value for a wide range of roadway and traffic conditions and checking for the logical validity of the results. For estimation of area-occupancy, it is necessary to measure accurately the characteristics of heterogeneous traffic flow and the other relevant factors on vehicular movement over a stretch of roadway. Measurement of these complex characteristics in the field is difficult and time consuming. Also, it may be difficult to carry out such experiments in the field covering a wide range of roadway and traffic conditions. Hence, it is necessary to model road–traffic flow for in depth understanding of the related aspects. The study of these complex characteristics, which may not be sufficiently simplified by analytical solution, can be done using appropriate modeling technique like computer simulation. Simulation is already proven to be a popular traffic-flow modeling tool for applications related to road-traffic-flow studies. Hence, simulation technique has been used here to validate the concept of area-occupancy.

7. Simulation Model

Simulation models may be classified as being static or dynamic, deterministic or stochastic, and discrete or continuous. A simulation model, which does not require any random values as input, is generally called *deterministic*, whereas a *stochastic* simulation model has one or more random variables as inputs. Random inputs lead to random outputs and these can only be considered as estimates of the true characteristics of the system being modeled. Discrete and continuous models are defined in an analogous manner. The choice of whether to use a discrete or continuous simulation model is a function of the characteristics of the system and the objectives of the study (Banks et al., 2004). For this study, a dynamic stochastic type discrete event simulation is adopted in which the aspects of interest are analysed numerically with the aid of a computer program.

As this study pertains to the heterogeneous traffic conditions prevailing in India, the available traffic-simulation program packages such as CORSIM, MITSIM, and VISSIM etc. cannot be directly used to study the characteristics of heterogeneous traffic flow as these are based on homogeneous traffic-flow conditions. Also, the research attempts made earlier (Katti & Raghavachari, 1986; Khan & Maini, 2000; Kumar & Rao, 1996; Marwah & Singh, 2000; Ramanayya, 1988) to simulate heterogeneous traffic flow on Indian roads were limited in scope as they were location and traffic-condition specific. Moreover, these studies did not truly represent the absence of lane and queue discipline in heterogeneous traffic. Hence, an appropriate traffic simulation model, named HETEROSIM has been developed at Indian Institute of Technology Madras, India (Arasan & Koshy, 2005) to replicate heterogeneous traffic flow conditions accurately.

The modelling framework is explained briefly here to provide the background for the study. For the purpose of simulation, the entire road space is considered as single unit and the vehicles are represented as rectangular blocks on the road space, the length and breadth of the blocks representing respectively, the overall length and the overall breadth of the vehicles (Figure 8). The entire road space is considered to be a surface made of small imaginary squares (cells of convenient size - 100 mm square in this case); thus, transforming the entire space into a matrix. The vehicles will occupy a specified number of cells whose co-ordinates would be defined before hand. The front left corner of the rectangular block is taken as the reference point, and the position of vehicles on the road space is identified based on the coordinates of the reference point with respect to an origin chosen at a convenient location on the space. 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.

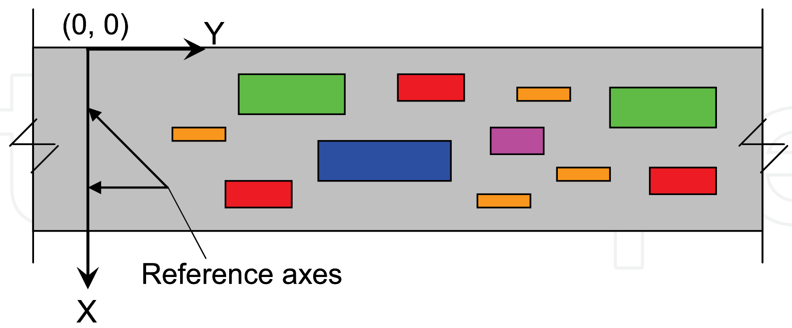


Fig. 8. Reference axes for representing vehicle positions on the roadway

The simulation model uses the interval scanning technique with fixed increment of time. For the purpose of simulation, the length of road stretch as well as the road width can be varied as per user specification. Due to possible unsteady flow condition at the start of the simulation stretch, a 200m long road stretch, from the start of the simulation stretch is used as warm up zone. Similarly, to avoid the possible unsteady flow at the end of the simulation stretch due to free exit of vehicles, a 200m long road stretch at the end of the simulation stretch is treated as tail end zone. Thus, the data of the simulated traffic flow characteristics are collected covering the middle portion between the warm up and tail end zones. The said details are shown in Figure 9.

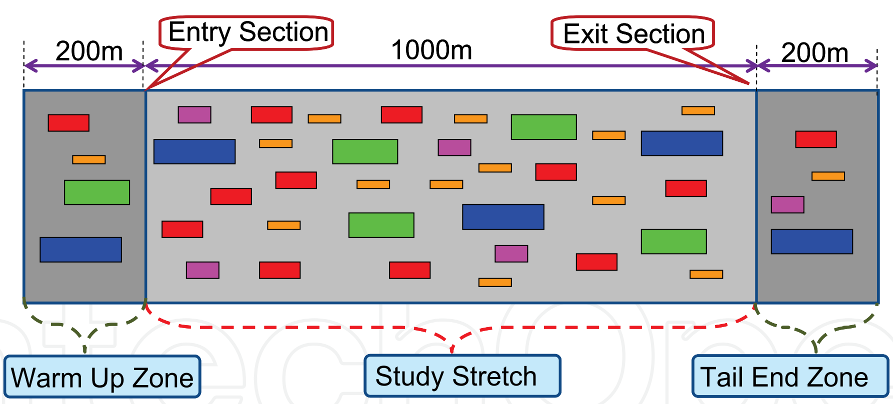


Fig.9. Road stretch considered for simulation of traffic flow

Also, to eliminate the initial transient nature of traffic flow, the simulation clock was set to start only after the first 50 vehicles reached the exit end of the road stretch. The model measures the speed maintained by each vehicle when it traverses a given reference length of roadway. The output also includes the number of each category of vehicles generated, the values of all the associated headways generated, number of vehicles present over a given length of road (concentration), number of overtaking maneuvers made by each vehicle, and speed profile of vehicles. The logic formulated for the model also permit admission of vehicles in parallel across the road width, since it is common for smaller vehicles such as Motorised two-wheelers to move in parallel in the traffic stream without lane discipline. The model was implemented in C++ programming language with modular software design. The flow diagram illustrating the basic logical aspects involved in the program is shown as Figure 10.

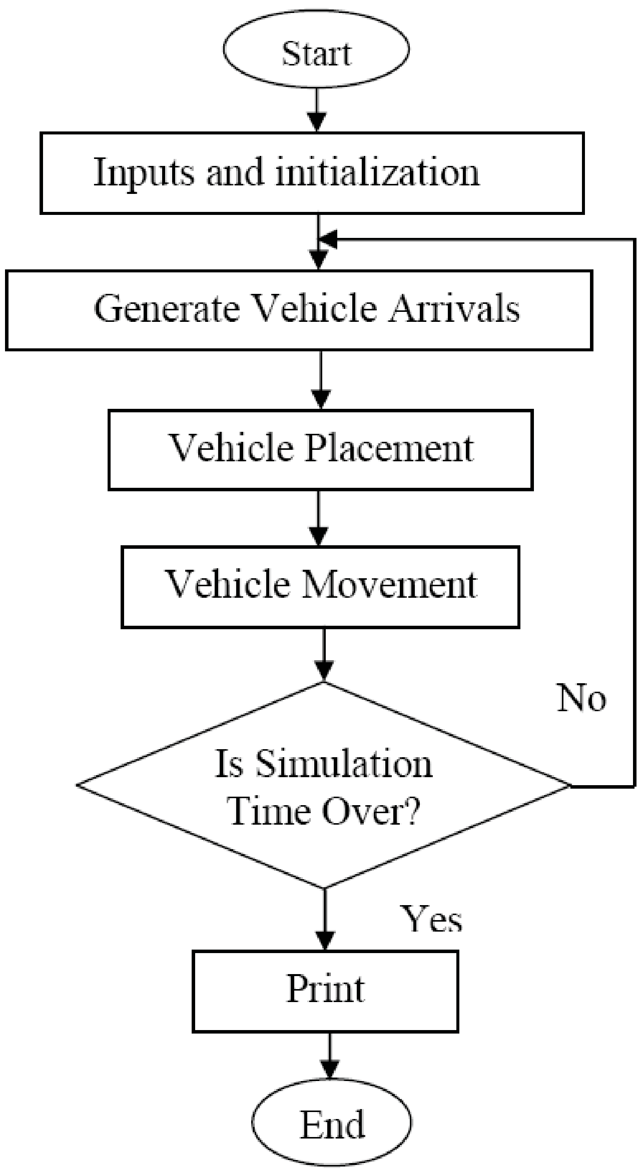


Fig.10. Major logical steps involved in the simulation model

The model is also capable of displaying the animation of simulated traffic movements through mid block sections. The animation module of the simulation model displays the model's operational behavior graphically during the simulation runs. The snapshot of animation of heterogeneous traffic flow, obtained using the animation module of HETEROSIM, is shown in Figure 11. The model has been applied for a wide range of traffic conditions (free flow to congested flow conditions) through an earlier study (Arasan & Koshy, 2005) and has been found to replicate the field observed traffic flow to a satisfactory extent.

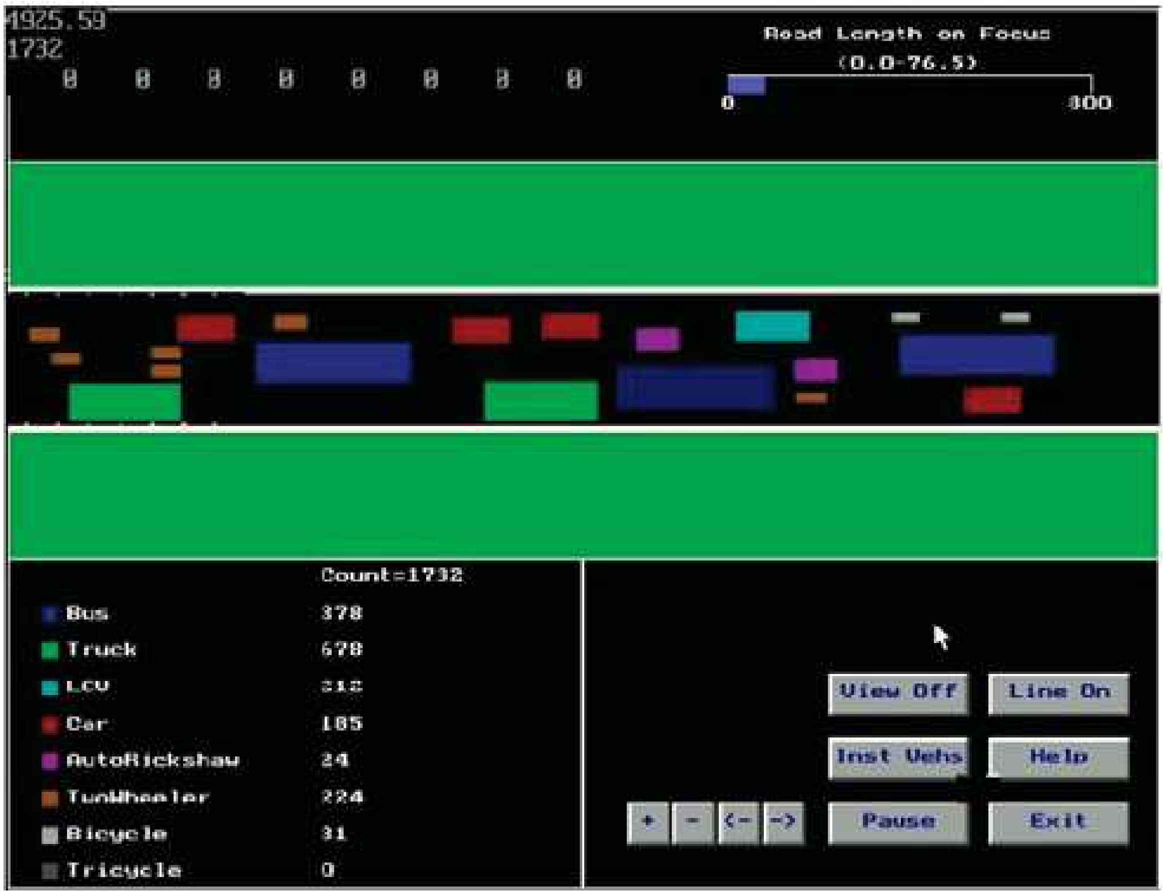


Fig. 11. Snapshot of the animation of simulated heterogeneous traffic flow

8. Validation of Area-Occupancy Concept

The concept of area-occupancy can be said to be applicable for any traffic stream under both heterogeneous and homogeneous traffic conditions. To check for the validity of the concept of area-occupancy, as the first step, the occupancy and area-occupancy of a homogeneous traffic stream are related independently to the density of a stream under homogeneous (cars-only) traffic condition for different lengths of detection zone. For this purpose, in respect of occupancy, the relationship between density and occupancy developed by Athol, 1965, given in equation (8) is used. In respect of area-occupancy, a relationship between density and area-occupancy under homogeneous traffic condition is newly developed, the details of which are given in the following sub-section.

8.1 Relationship between Density and Area-Occupancy

The relationship between density and area-occupancy is derived as follows:
During the time interval $(t_i)_{AO}$, let the distance traveled by a vehicle with speed u_i be L. Then, substituting $(t_i)_{AO} = L/u_i$ in equation (10), we get,

$$\text{Area-Occupancy, } \rho_A = \frac{\sum_i a_i \times (L/u_i)}{A \times T} \tag{11}$$

Under highly homogeneous traffic condition, a_i can be considered to be the same, say *a*, for all vehicles and hence, equation (11) can be written as,

$$\rho_A = \frac{a}{A} \times \frac{L}{T} \times \sum_i \frac{1}{u_i} \tag{12}$$

Multiplying and dividing the right hand side of equation (12) by the total number of vehicles, denoted by *N*, the expression will become,

$$\rho_A = \left(\frac{a}{A} \times L\right) \times \left(\frac{N}{T}\right) \times \left(\frac{1}{N}\right) \times \sum_i \left(\frac{1}{u_i}\right) \tag{13}$$

The space mean speed of a traffic stream, as per equation (2), is,

$$u_s = \frac{1}{\frac{1}{N}\sum_i \frac{1}{u_i}} \tag{14}$$

Also, the flow of a traffic stream, as per equation (1), is,

$$q = \frac{N}{T} \tag{15}$$

Then, using equations (14) and (15), equation (13) can be written as,

$$\rho_A = \left(\frac{a}{A} \times L\right) \times \left(\frac{q}{u_s}\right) \tag{16}$$

As per Equation (6), (q/u_s) is equal to *k*, and hence, the relationship between density and area-occupancy, under homogeneous traffic condition, from equation (16), can be obtained as,

$$\rho_A = \left(\frac{a}{A} \times L\right) \times k \tag{17}$$

When the length of the detection zone *(d)* is less than the vehicle length (*l*), then, the distance travelled by a vehicle in time, $(t_i)_{AO}$ is *l* and the value of *a* is *d* multiplied by *w* and hence, the relationship between area-occupancy and density, from equation (17), in this case, can be given as,

$$\rho_A = \left(\frac{d \times w}{d \times W} \times l\right) \times k$$

That is,

$$\rho_A = \left(\frac{a_v}{W}\right) \times k \tag{18}$$

where, w = width of the vehicle;
W = width of the detection zone;
a_v = area of the vehicle.

When the length of the detection zone is more than the vehicle length ($d > l$), then, the distance traveled by a vehicle in time, $(t_i)_{AO}$ is d and the value of a is l multiplied by w and hence, the relationship between area-occupancy and density, from equation (17), in this case, can be given as,

$$\rho_A = \left(\frac{l \times w}{d \times W} \times d\right) \times k$$

That is,

$$\rho_A = \left(\frac{a_v}{W}\right) \times k \tag{19}$$

Thus, it is clear from equations (18) and (19) that the value of area-occupancy for a given roadway and traffic conditions is unaffected by change in the length of detection zone. This mathematical result can also be cross checked by performing traffic simulation experiments and the simulation experiments are explained in the following section.

8.2 Simulation Experiment

Since the scope of the experiment is to prove a fundamental relationship, uniform traffic flow on a single traffic lane was considered. Accordingly, the HETEROSIM model was used for simulating the cars-only traffic (100% passenger cars of assumed length 4 m and width 1.6 m) on a 3.5m wide road space - single traffic lane (with no passing). The traffic flow was simulated for one hour (T = 1h) over a stretch of one km. The simulation runs were made with three random number seeds and the averages of the three values were taken as the final model output. The simulation was also run with various volume levels for various lengths (1m, 2m, 3m and 4m) of detection zone. Using the features of the simulation model, the times $(t_i)_O$ and $(t_i)_{AO}$ were recorded for each of the simulated vehicles, (assuming the speed maintained by the vehicles on the detection zone is constant) and the values are given in columns (3) and (4) of Table 2. It may be noted that the distance traveled by the vehicle during time $(t_i)_{AO}$ is l, which is constant for all the vehicles under homogeneous traffic condition and hence, the time $(t_i)_{AO}$ remains unchanged for the different lengths of detection zone for a given traffic volume. The occupancy and area-occupancy were then calculated using equations (9) and (10) respectively and the values are shown in columns (5) and (6) of Table 2. Density was then estimated using equation (8) as well as equation (18). The density values, thus calculated, are given in columns (7) and column (8) of Table 2.
It can be seen that the density values estimated from the relationship with area-occupancy (equation (18)) is the same as those estimated from the relationship with occupancy (equation (8)). This implies that area-occupancy can be a substitute for occupancy.

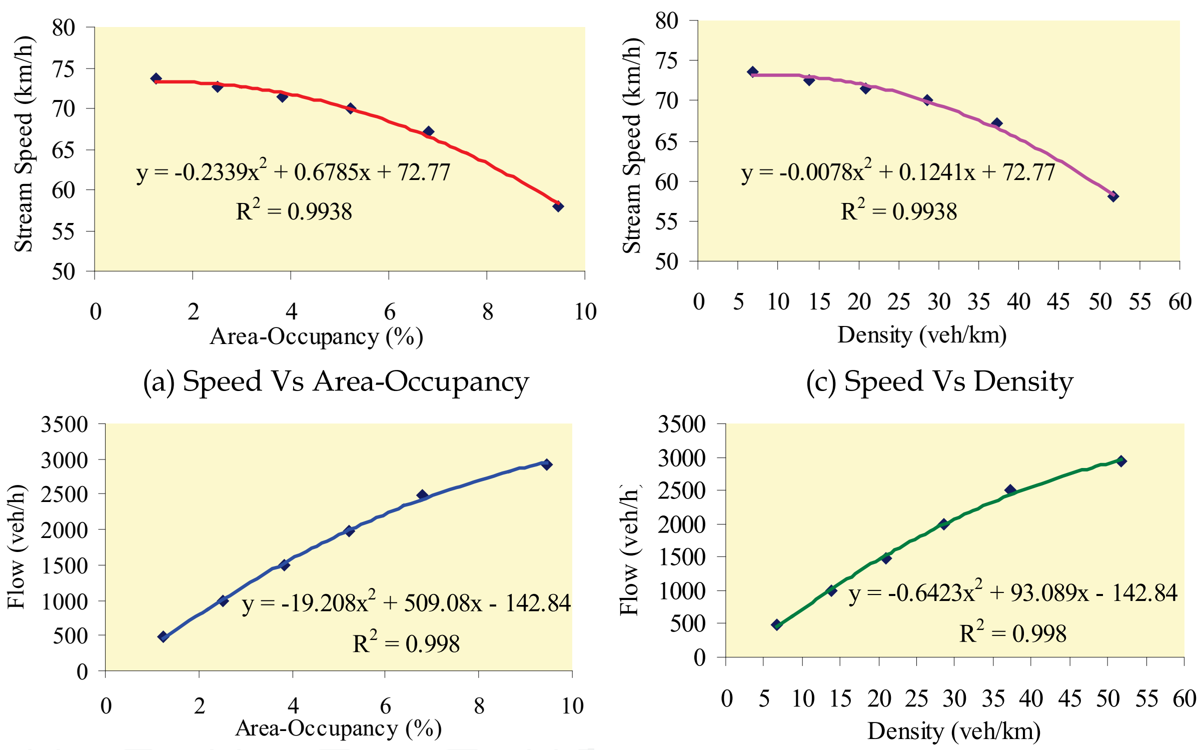
Flow (veh./h) (1)	Mean Speed (km/h) (2)	$(t_i)_O$ (s) (3)	$(t_i)_{AO}$ (s) (4)	Occupancy[a] (%) (5)	Area-Occupancy[x] (%) (6)	Density (veh./km) obtained as $k = \frac{\rho}{(l+d)}$ (7)	Density (veh./km) obtained as $k = \frac{\rho_A}{(C \times l)}$ (8)
Length of detection zone: 1m							
494	73.68	122.16	97.72	3.39	1.24	7	7
989	72.59	247.96	198.37	6.89	2.52	14	14
1487	71.46	377.84	302.27	10.50	3.84	21	21
1988	69.99	514.33	411.47	14.29	5.22	29	29
2495	67.19	669.74	535.79	18.60	6.80	37	37
2930	58.03	930.59	744.47	25.85	9.45	52	52
Length of detection zone: 2m							
494	73.68	146.59	97.72	4.07	1.24	7	7
989	72.59	297.56	198.37	8.27	2.52	14	14
1487	71.46	453.41	302.27	12.59	3.84	21	21
1988	69.99	617.20	411.47	17.14	5.22	29	29
2495	67.19	803.68	535.79	22.32	6.80	37	37
2930	58.03	1116.71	744.47	31.02	9.45	52	52
Length of detection zone: 3m							
494	73.68	171.02	97.72	4.75	1.24	7	7
989	72.59	347.15	198.37	9.64	2.52	14	14
1487	71.46	528.98	302.27	14.69	3.84	21	21
1988	69.99	720.07	411.47	20.00	5.22	29	29
2495	67.19	937.63	535.79	26.05	6.80	37	37
2930	58.03	1302.83	744.47	36.19	9.45	52	52
Length of detection zone: 4m							
494	73.68	195.45	97.72	5.43	1.24	7	7
989	72.59	396.74	198.37	11.02	2.52	14	14
1487	71.46	604.54	302.27	16.79	3.84	21	21
1988	69.99	822.93	411.47	22.86	5.22	29	29
2495	67.19	1071.58	535.79	29.77	6.80	37	37
2930	58.03	1488.94	744.47	41.36	9.45	52	52

[a]obtained by multiplying the occupancy value obtained, using equation (9), by 100.
[x]obtained by multiplying the area-occupancy value obtained, using equation (10), by 100.

Table 2. Estimated values of occupancy, area-occupancy and density of homogeneous traffic

It can also be seen that the occupancy values (column (5) in Table 2) estimated for the detection zone lengths of 1, 2, 3, and 4 m are significantly different from one another for a given traffic volume level. Thus, it is clear that even a small change (1m) in detection-zone length results in a considerable change in the value of occupancy corroborating the fact that occupancy is specific to the length of the detection zone. On the other hand, the area-occupancy (column (6) in Table 2) remains unchanged for the different lengths of detection zone for a given volume of traffic. This implies that the concept of area-occupancy is valid for any length of detection zone. Hence, area-occupancy can be applied to measure accurately the extent of usage of road space by vehicles without any restriction on the length of detection zone.

Also, to depict the validity of area-occupancy as replacement for density (concentration), the results of the simulation experiment (Table 2) were used to make plots relating (i) area-occupancy with speed and flow and (ii) density with speed and flow as shown in Figure 12. It can be seen that area-occupancy and density exhibit similar trends of relationships with speed and flow.



(b) Flow Vs Area-Occupancy (d) Flow Vs Density

Fig. 12. Relationship between traffic flow characteristics

9. Area-Occupancy of Heterogeneous Traffic

The concept of area-occupancy can be applied as indicated earlier, for heterogeneous traffic condition also and relationships can be developed between flow, area-occupancy and traffic stream speed. The relationship is derived as follows:

The formula for area-occupancy of heterogeneous traffic, from equation (10), can be written as,

$$\rho_A = \frac{\sum_{j=1}^{n} a_j \sum_i \left(t_{ji}\right)_{AO}}{AT} \tag{20}$$

where, j = vehicle category;

i = subject vehicle within category j;

a_j = horizontal projected area of the vehicle of category j falling on the detection zone;

T = observation period;

A = area of the detection zone;

n = total number of vehicle categories in the heterogeneous traffic.

Therefore, for each substream j,

$$\left(\rho_A\right)_j = \frac{a_j \sum_i \left(t_i\right)_{AO}}{TA} \tag{21}$$

As the area of vehicle category j is constant for all the vehicles with in that category, equation (21) can be written as,

$$\left(\rho_A\right)_j = \left(\frac{a_j}{A}\right) \frac{\sum_i \left(t_i\right)_{AO}}{T} \tag{22}$$

During the time interval $(t_i)_{AO}$, let the distance traveled by a vehicle of category j with speed u_i be L. Then, substituting $(t_i)_{AO} = L/u_i$ in equation (22), and multiplying and dividing the right hand side of the equation by the total number of vehicles of category j, N_j, the expression will become,

$$\left(\rho_A\right)_j = \left(\frac{a_j}{A}\right) \times \left(\frac{N_j}{N_j}\right) \times \frac{\sum_i \left(\frac{L}{u_i}\right)}{T}$$

That is,

$$\left(\rho_A\right)_j = L \times \left(\frac{a_j}{A}\right) \times \left(\frac{N_j}{T}\right) \times \frac{1}{N_j} \sum_i \left(\frac{1}{u_i}\right) \tag{23}$$

The space mean speed of sub stream j, (u_j) can be expressed as

$$u_j = \frac{1}{\frac{1}{N_j} \sum_i \frac{1}{u_i}} \tag{24}$$

Also the flow of sub stream j (q_j) can be written as

$$q_j = \frac{N_j}{T} \tag{25}$$

Hence, using equations (24) and (25), equation (23) can be written as,

$$(\rho_A)_j = L \times \left(\frac{a_j}{A}\right) \times \frac{q_j}{u_j} \tag{26}$$

When the length of the detection zone *(d)* is less than the vehicle length *(l)* then, the distance traveled by a vehicle *(L)* is *l*, when ($d < l$) and d when ($d > l$). The value of a_i is ($d \cdot w$) when ($d < l$) and ($l \cdot w$) when ($d > l$) and then equation (26) can be simplified as,

$$(\rho_A)_j = \left(\frac{a_{vj}}{W}\right) \times \frac{q_j}{u_j} \tag{27}$$

where, W = width of the detection zone;
a_{vj} = area of the vehicle category j.

for both the cases, namely, ($d < l$) and ($d > l$) as for the steps followed to derive equations (18) and (19).
Then, the area occupancy of whole of the traffic stream is

$$\rho_A = \sum_j (\rho_A)_j \tag{28}$$

Hence, it is clear from equation (27) that by knowing the flow and speed of the different categories of vehicles in a heterogeneous traffic stream, the area-occupancy of different susbstreams can be calculated. Also, the area-occupancy of the whole of the traffic stream can be calculated using the relationship given in equation (28).
Under heterogeneous traffic condition, there may be several substreams, each with different vehicle categories in the whole of the traffic stream. Hence, to determine the area-occupancy of the whole of the traffic stream and subsequently to formulate relationship between area-occupancy, flow and speed for the traffic stream as a whole, it is necessary to express the area-occupancy value of each of the substreams in terms of area-occupancy of an equivalent stream consisting of a standard vehicle. The same can be written, based on equation (27), mathematically, as,

$$\frac{a_{sv} \times (q_{sv})_j}{W \times (u_{sv})_j} = \frac{a_{vj} \times q_j}{W \times u_j} \tag{29}$$

where, $(q_{sv})_j$ = flow of standard vehicle, equivalent to substream j, expressed in No. of vehicles/h;
$(u_{sv})_j$ = space mean speed of the standard vehicles with flow $(q_{sv})_j$;
a_{sv} = area of the standard vehicle;

Equation (29) can be simplified as,

$$\frac{(q_{sv})_j}{(u_{sv})_j} = \frac{\left(\frac{a_{vj}}{a_{sv}}\right) \times q_j}{u_j} \quad (30)$$

Multiplying and dividing the right hand side of equation (27) by a_{sv}, we get,

$$(\rho_A)_j = \left(\frac{a_{sv}}{W}\right) \times \frac{\left(\frac{a_{vj}}{a_{sv}}\right) \times q_j}{u_j} \quad (31)$$

From equation (30), equation (31) can be written as,

$$(\rho_A)_j = \left(\frac{a_{sv}}{W}\right) \times \frac{(q_{sv})_j}{(u_{sv})_j} \quad (32)$$

From equation (27), the area of occupancy of traffic stream considered in terms of standard vehicles with flow q_{sv} can be written as

$$\rho_A = \left(\frac{a_{sv}}{W}\right) \times \frac{q_{sv}}{u_{sv}} \quad (33)$$

Also,

$$q_{sv} = \sum_j (q_{sv})_j \quad (34)$$

Where, ρ_A = area-occupancy of the whole of the traffic stream considered in terms of standard vehicle;
q_{sv} = flow of the whole of the traffic stream considered in terms of standard vehicles;
u_{sv} = space mean speed of the whole of the stream considered in terms of standard vehicle.

From equation (28), equation (33) can be written as

$$\rho_A = \sum_j (\rho_A)_j = \left(\frac{a_{sv}}{W}\right) \times \frac{q_{sv}}{u_{sv}} \quad (35)$$

From equation (32), equation (35) can be written as,

$$\left(\frac{a_{sv}}{W}\right) \sum_j \frac{(q_{sv})_j}{(u_{sv})_j} = \frac{\left(\frac{a_{sv}}{W}\right) \times q_{sv}}{u_{sv}}$$

That is,

$$u_{sv} = \frac{\left(\frac{a_{sv}}{W}\right) \times q_{sv}}{\left(\frac{a_{sv}}{W}\right) \sum_j \frac{(q_{sv})_j}{(u_{sv})_j}} \tag{36}$$

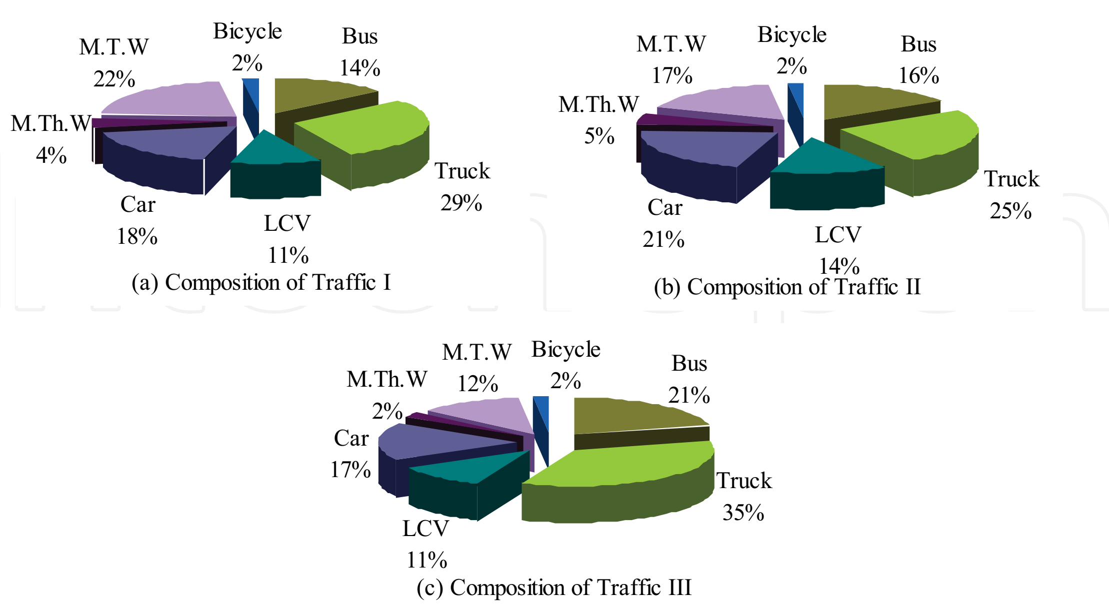
From equation (34), the stream speed of traffic considered in terms of standard vehicles (equation (36)) can be written as,

$$u_{sv} = \frac{\sum_j (q_{sv})_j}{\sum_j \frac{(q_{sv})_j}{(u_{sv})_j}} \tag{37}$$

If heterogeneous traffic is converted into equivalent standard vehicles based on the concept of area-occupancy (by satisfying the condition given in equation (29)), then, equation (33) is the fundamental equation of heterogeneous traffic flow in which flow is expressed in terms of standard vehicles.

10. Application through Simulation

As the concept of area-occupancy takes into account the variations in traffic composition, it remains unaffected by change in traffic composition. To validate this statement, heterogeneous traffic with three different compositions, as shown in Figure 13 were considered.



LCV- Light Commercial Vehicle, M.Th.W – Motorised Three-Wheelers, M.T.W - Motorised Two-Wheelers

Fig. 13. Composition of the three different heterogeneous traffic streams

The traffic flow was simulated on a six lane divided road with 10.5m wide main carriageway and 1.5m of paved shoulder for various volume levels, for each of the three cases. The traffic flow was simulated on one km long road stretch for one hour and three simulation runs, with different random number seeds, were made and the mean values of the three runs were taken as the final values of the relevant parameters obtained through the simulation process. Using the features of the simulation model, the time $(t_i)_{AO}$ was recorded for each of the simulated vehicles, considering a detection-zone of length 3m. The area-occupancy was estimated using the equation (20) (It can also be estimated using the equations (27) and (28)). In this case, the area of the detection zone is equal to (3 X 12 = 36 m^2). The value of area-occupancy of traffic for the three different traffic compositions were plotted, on a single set of axes, against V/C ratio, and the same is depicted in Figure 14. It can be seen that the values of area-occupancy of the three heterogeneous traffic streams are nearly the same for any given flow (V/C) level and it can be concluded that the area-occupancy can be used as a measure of traffic concentration for any traffic and roadway condition.

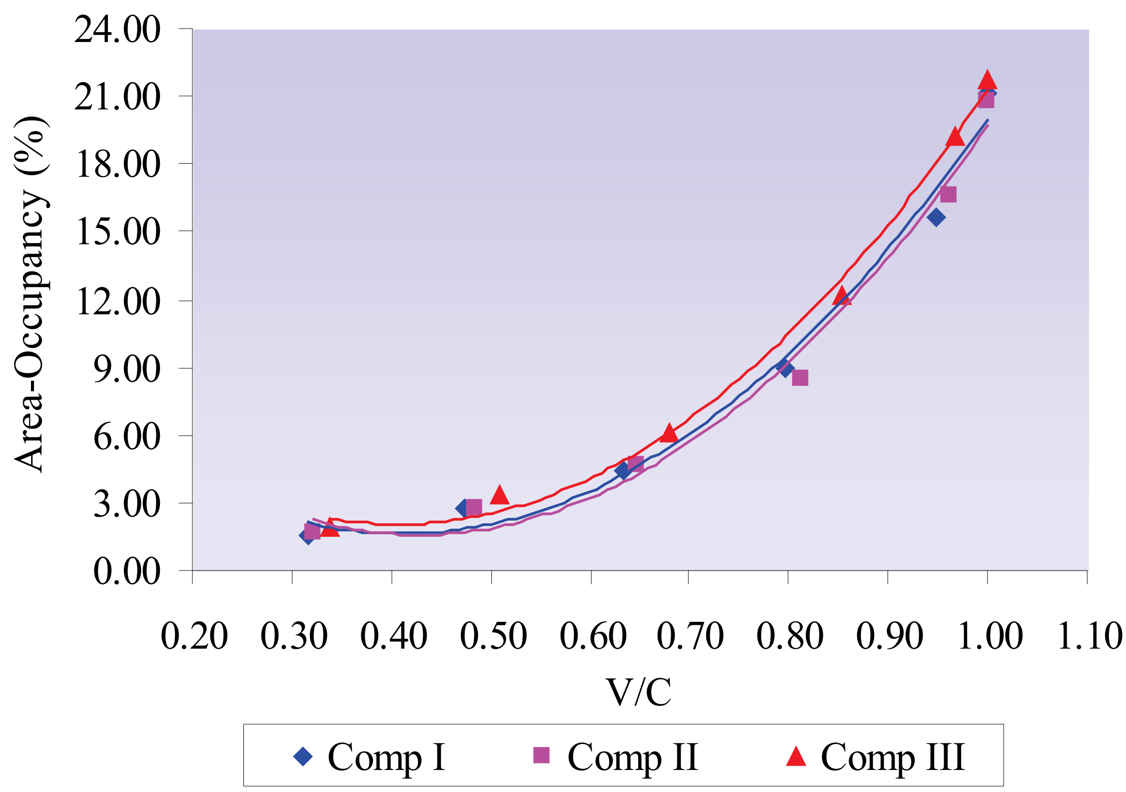
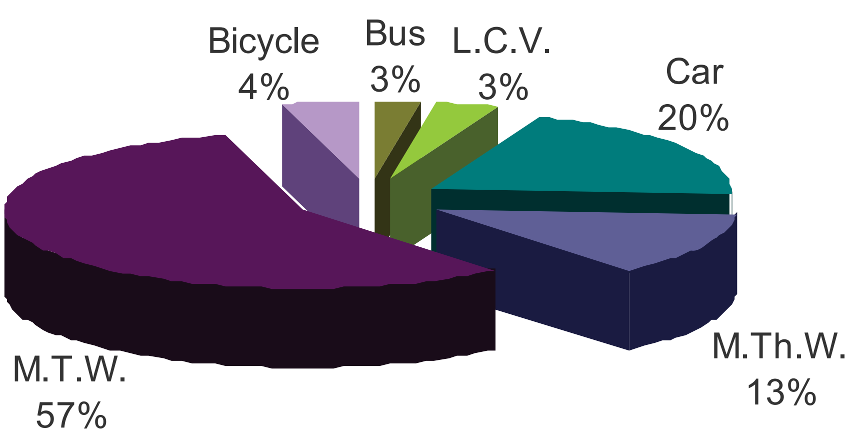


Fig. 14. Relationship between area-occupancy and V/C ratio

10.1 Relationship between Traffic-Flow Characteristics

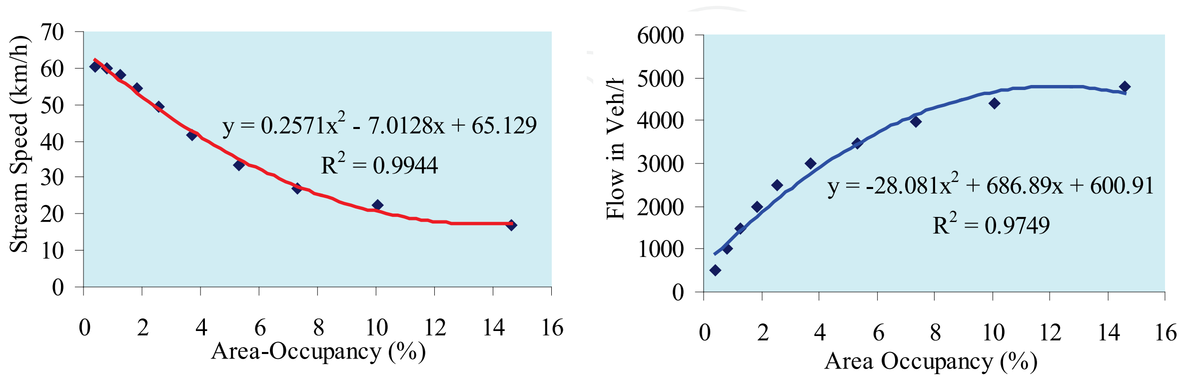
To reinforce the fact that the concept of area-occupancy can be applied to study the various characteristics of heterogeneous traffic flow, the area-occupancy of heterogeneous traffic was estimated by simulating one-way flow of heterogeneous traffic on a 7.5 m wide road (equivalent to one half of four-lane divided road) for various volume levels with the representative traffic composition prevailing on urban roads in India (depicted in Figure 15). The traffic flow was simulated on one km long road stretch for one hour and three simulation runs, with different random number seeds, were made and the mean values of the three runs were taken as the final values of the relevant parameters obtained through the simulation process. Using the features of the simulation model, the time $(t_i)_{AO}$ was recorded for each of the simulated vehicles, considering a detection zone of length 3m.



LCV- Light Commercial Vehicle, M.Th.W – Motorised Three-Wheelers, M.T.W - Motorised Two-Wheelers

Fig. 15. Representative composition of the traffic prevailing on urban roads in India

The area-occupancy was estimated using the equation (20). In this case, the area of the detection zone is equal to (3 X 7.5 = 22.5 m^2). The average stream speeds and exit volume of the heterogeneous traffic, for the various volume levels were then obtained using the simulation output. Then, plots relating the area-occupancy, speed and flow were made as shown in Figure 16. It may be noted that there is decrease in speed with increase in area-occupancy (Figure 16(a)) and increase in traffic flow with increase in area-occupancy (Figure 16(b)), which are logical indicating the appropriateness of the area-occupancy concept for heterogeneous traffic. Hence, it is inferred that the concept of area-occupancy is valid and can be applied to measure accurately the traffic concentration.



(a) Speed Vs area-occupancy (b) Flow Vs area-occupancy

Fig. 16. Relationship between area-occupancy, flow and speed

11. Summary and Conclusion

Concentration is a traffic measure which explains the extent of usage of road space by vehicles. It is a broader term encompassing both density and occupancy. The first is a measure of concentration over space; the second measures concentration over time of the same vehicle stream. The review of the literature on traffic flow characteristics indicates that the traffic density, expressed as number of vehicles per unit length of roadway, can not be appropriate for accurate measurement of traffic concentration, due to variation in the dimensions and speed of vehicles, even on a given traffic lane. Hence, there is a need for development of an appropriate alternative measure to represent traffic concentration with potential for application to traffic conditions where there is significant difference in speed and dimensions of vehicles.

Occupancy, defined as the proportion of time during which the detection zone on a highway is covered by all vehicles, can help to remove the deficiencies of the concept of density to a significant extent. Occupancy, thus, takes into account the traffic composition (variation in the dimensions of vehicles) and speed variations, in its measurement, simultaneously and gives a more reliable indicator of the extent of road being used by vehicles. Hence, occupancy is more meaningful than density. Since, occupancy depends on the size of the detection zone, the measured occupancy, however, may be different for different detection-zone lengths, even for the same roadway and traffic conditions. Also, the concept of occupancy can not be directly applied under highly heterogeneous traffic conditions such as those prevailing on Indian roads, as the traffic has no lane discipline (vehicles occupy any lateral position on the road depending on the availability of road space at a given instant of time) and hence, it is necessary to consider the whole of the road as single unit to analyze the traffic flow.

Hence, a new measure, named, 'area-occupancy' is proposed, which considers the horizontal projected area of the vehicle, without any restriction on the length of the detection zone and width of road (treating the whole of the width of road as single unit without consideration of traffic lanes) as the bases. Thus, on a stretch of road, area-occupancy is expressed as the proportion of the area of the detection zone covered by all the vehicles, traversing the zone during the observation time. The area-occupancy is not affected by the length of the detection zone since it considers the length of the detection zone in its formulation. Also, the effect of heterogeneity and lane less nature of the traffic is incorporated in the concept of area-occupancy by consider the horizontal projected area (length and width) of the vehicle in its formulation. Hence, the concept of area-occupancy is valid to measure, accurately, the extent of usage of road space by vehicles. It may be noted that the area-occupancy concept can be applied to any traffic condition, from highly homogeneous to highly heterogeneous, and to any length of the detection zone.

To check for the validity of the concept, the occupancy and area-occupancy of a homogeneous traffic stream were estimated for different lengths of detection zone through simulation experiments and the values were related to the density of the stream. It was found from the results of the simulation experiment, that area-occupancy can be a substitute for occupancy. Also, the estimated area-occupancy is found to remain unchanged with respect to change in the length of the detection zone. Thus, it has been proved that area-occupancy, rather than occupancy, can be used as indicator of road traffic concentration at any flow level because of its ability to accurately replicate the extent of usage of the road space. Also, to depict the validity of area-occupancy as replacement for density (concentration), plots relating (i) area-occupancy with speed and flow and (ii) density with speed and flow were made and it was found that area-occupancy and density exhibit similar trends of relationships with speed and flow.

It was found through simulation experiments that the area-occupancy remains stable with respect to change in traffic composition under heterogeneous traffic conditions. Also, relationships between flow, speed and area-occupancy of heterogeneous traffic for a most common roadway and traffic conditions prevailing in India have been developed and found to be logical. This further reinforces the fact that area-occupancy is an appropriate measure of traffic concentration for any roadway and traffic conditions.

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Advanced Technologies

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This book, edited by the Intech committee, combines several hotly debated topics in science, engineering, medicine, information technology, environment, economics and management, and provides a scholarly contribution to its further development. In view of the topical importance of, and the great emphasis placed by the emerging needs of the changing world, it was decided to have this special book publication comprise thirty six chapters which focus on multi-disciplinary and inter-disciplinary topics. The inter-disciplinary works were limited in their capacity so a more coherent and constructive alternative was needed. Our expectation is that this book will help fill this gap because it has crossed the disciplinary divide to incorporate contributions from scientists and other specialists. The Intech committee hopes that its book chapters, journal articles, and other activities will help increase knowledge across disciplines and around the world. To that end the committee invites readers to contribute ideas on how best this objective could be accomplished.

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InTech Europe
University Campus STeP Ri
Slavka Krautzeka 83/A
51000 Rijeka, Croatia
Phone: +385 (51) 770 447
Fax: +385 (51) 686 166
www.intechopen.com

InTech China
Unit 405, Office Block, Hotel Equatorial Shanghai
No.65, Yan An Road (West), Shanghai, 200040, China
中国上海市延安西路65号上海国际贵都大饭店办公楼405单元
Phone: +86-21-62489820
Fax: +86-21-62489821