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ORIGINAL ARTICLE

Review of Studies on Mixed Traffic Flow: Perspective of Developing Economies

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Abstract The traffic scenario in developing economies is fundamentally different from that of the developed economies. The latter is predominantly composed of passenger cars and can be aptly termed as "homogeneous" traffic, whereas the former is composed of vehicle types with a wide variety of static and dynamic characteristics, which occupy the same right of way, resulting in an unsynchronized movement of the vehicles. Another distinguishing characteristic of this traffic is the absence of lane-discipline, resulting from the wide variation in sizes and maneuvering abilities of the vehicles. These distinctions result in some phenomena like vehicle creeping, which are absent in the homogeneous traffic. Hence, this type of traffic can be referred to as "heterogeneous disordered" or "mixed" traffic. A review of the literature has shown that most of the studies in such traffic make use of the methods and concepts developed for homogeneous traffic. Very few studies have attempted to capture and understand the distinctive characteristics of the mixed traffic. The primary objective of this paper is to provide a review of the studies on various mixed traffic characteristics in developing economies, identify their limitations and provide guidelines for the future research. Also, a detailed methodology of the simulation process for the mixed traffic is given, reflecting the "gap-filling" rather than the conventional "car-following" behavior. A comparison of the past modeling approaches is also presented and the accuracy of their implementation is discussed.

keywords Heterogeneous · Traffic characteristics · Modeling · PCU · Area occupancy

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Introduction

Starting with Greenshields' studies [24] as far back as in 1935, considerable research effort has been spent to understand the traffic flow characteristics in developed economies. In 1960s, Car following theory was developed, with the background of the experiments conducted by researchers at the General motors' research laboratory. Lighthill and Whitham [43] and Richards [74] proposed a continuum model for vehicular flow based on an analogy with fluid flow and laid the foundation for "macroscopic traffic flow modeling". Later empirical studies have identified various traffic phenomena including stop-and-go waves, hysteresis effect, phantom jams and capacity drop. Analogies with other physical systems are used to describe these phenomena. These studies have resulted in a traffic flow theory with a strong mathematical and empirical basis, which is essential for a thorough understanding of the traffic dynamics.

The above studies are aimed at understanding the traffic in developed economies, which is predominantly composed of passenger cars and is called "homogeneous" traffic. However, the traffic in other developing economies have a significant share of two and three-wheeler motorized vehicles and non-motorized vehicles with different static and dynamic characteristics, resulting in a fundamentally different traffic stream. Because of the differences in sizes and maneuverabilities, the vehicles in this traffic stream do not follow the lane-discipline, whereas the homogeneous traffic has strict lane-discipline. Incidentally, the term "heterogeneous" is used in the literature, to describe the traffic consisting of heavy vehicles, as observed in some areas of the developed economies. However, this traffic has a relatively small proportion of heavy vehicles and still follows strict lane-discipline. Therefore, to avoid the confusion, the traffic in developing economies described above can be referred to as "heterogeneous disordered" or "mixed" traffic.

Naturally, with the differences pointed out above, the traffic flow theory developed for homogeneous traffic is not applicable for the mixed traffic conditions, without significant modifications. However, much of the latter's current theory and models directly use the concepts developed, essentially, for homogeneous traffic. In fact, the validity of these concepts has been questioned in recent times and attempts have been made to introduce new or modified ideas more appropriate for the mixed traffic conditions. But, there is still a great deal of work to be done to address the deficiencies in the current practices. At this point, it is advisable to look at the past research to plan our future research efforts. With this objective, a comprehensive review of the research in various characteristics and the modeling of the mixed traffic are presented in this paper. The last such attempt was made by Khan and Maini [35] but the primary focus of that paper were the macroscopic flow relationships and micro-simulation models. Also, there has been a considerable advancement in the understanding of mixed traffic characteristics, since then. This paper attempts to review all those studies, identify their limitations and provide guidelines for the future research.

Our aim, however, is not to give a detailed presentation of the methodology used and the numerical results in each study, but to cover the breadth of the studies on mixed traffic. Only a brief summary of these studies is given in each topic, along with a commentary on their deficiencies and the scope for the future research. Each of the following sections reviews the studies on different topics namely, vehicle characteristics, passenger car equivalents (PCEs), lateral characteristics, capacity and level of service, saturation flow and modeling. A few concluding comments are made in the final section, with some suggestions for the future research.

Vehicle Characteristics

The traffic in developing economies is composed of vehicles with wide variation in physical and performance characteristics. These vehicles include cars, buses, trucks, auto-rickshaws (three-wheelers), motorized two wheelers and other non-motorized vehicles like bicycles, human and animal-driven carts. The fact that these vehicles share the same right of way results in some characteristic features that are absent in the homogeneous traffic conditions. Along with the most prominent weak lane-discipline behavior, these features include the differences in driver behaviors of different types of vehicles and impacts of these vehicles on the traffic stream as a whole. Hence, to study the heterogeneous or mixed traffic in developing economies, it is essential to understand the characteristics of each vehicle type and their resulting behavior in the traffic stream.

Classification and Sizes of the Different Vehicle Types

Depending on the traffic composition at the study location, researchers classify the vehicles into different categories. This classification serves two purposes:

1. To group the vehicles with similar characteristics and reduce the extra burden of considering each vehicle type with no significant share in the traffic by itself.
2. To allow the usage of standard values for their characteristics available in the literature.

However, care must be taken to avoid vehicles with significantly different characteristics to be grouped into the same category [55, 56]. Multiple sources exist in the literature for these standard categories and their average dimensions [6, 16, 45]. Fortunately, these values agree with each other strengthening their reliability. Vehicle dimensions given by Chandra and Kumar [16] have been widely adopted in the studies of various developing economies [12, 21, 61] and are given below (Table 1).

Speed and Acceleration Characteristics

Speed is a fundamental measure in determining various performance and operational characteristics of a highway system like, quality of service, regulation and control of traffic, etc. Together with density and flow, speed forms the fundamental relation which is the basis for many traffic flow models for homogeneous conditions. However, the idea is not as straight-forward in the mixed traffic. To start with, the average speeds of different categories of vehicles vary significantly. A relatively high variation is found even within a particular category, because of the different vehicle models present in it. Unlike the homogeneous and lane-disciplined traffic, where the car-following theory is generally used to determine a vehicle's speed, in mixed traffic, the effect of the interaction of other vehicles on the subject vehicle is hard to quantify, as it is affected by the traffic stream as a whole and the road conditions.

Table 1 Vehicle categories and their average dimensions

Category	Vehicles included	Average dimension (m)		Projected rectangular area on ground (m^2)
		Length (m)	Width (m)	
Car	Car, jeep	3.72	1.44	5.39
Bus	Bus	10.1	2.43	24.74
Truck	Truck	7.5	2.35	17.62
LCV	Mini bus, vans	6.1	2.10	12.81
Tractor	Tractor trailer	7.4	2.20	16.28
Three-wheeler	Three wheeler	3.2	1.40	4.48
Two-wheeler	Scooter, motorbike	1.87	0.64	1.2
Cycle	Bicycles	1.9	0.45	0.85
Rickshaw	Pedal rickshaw/cart	2.7	0.95	2.56

Nevertheless, several attempts have been made in the past to include these effects, whose summary is given below.

Several previous studies have shown that free-speeds of each vehicle category follow normal distribution on different types of highways [28, 32, 34, 40, 77]. Hossain and Iqbal [28] carried out a regression analysis to explore the relationship between free-speed and the shoulder width. It was observed that in the case of buses, this does not strongly correlate with the shoulder width. Sarna et al. [78] and Kumar and Madhu [41] observed that the traffic stream speed decreases with an increase in the proportion of auto-rickshaws. The 85th percentile speed is taken as a better estimate of the free speed in some studies [2, 41]. Dey et al. [18] proposed unimodal and bimodal curves for the speed distribution in mixed traffic. A new measure called spread ratio is proposed to identify which curve a given data follows. It is defined as the ratio of the difference between 85th percentile and the mean stream speed to the difference between mean stream speed and the 15th percentile speed. The speed data is found to follow the unimodal curve only when the spread ratio is within certain range. As different vehicle categories follow normal distribution with different mean speeds, it is not surprising to see the speed data with multiple peaks. However, researchers have observed that, at higher volumes, the high performance vehicles are obstructed by low performance ones and the stream behaves as a single platoon, with relatively constant speed [45]. These speed–flow relationships must be explored further, to see if the speed distribution curves and spread ratio can help in identifying this phenomenon. Other modeling attempts of speed include Dhamaniya and Chandra [21], who proposed a set of simultaneous equations, relating speeds of each vehicle type to all the individual densities. Another speed relation proposed by Nagaraj et al. [64] relates it to the lateral clearances requirements of the vehicles. Also, note that the general method of collecting speed data in the above studies is by selecting a longitudinal road stretch of a given length and taking the speed in this stretch as the average of the entire road section.

In mixed traffic, acceleration rates of the vehicles at high densities are as important as their desired speeds at lower densities. The gap-filling behavior of the vehicles leads to their role in determining the overtaking/passing maneuvers under the given road and traffic conditions. Along with these conditions, the factors affecting the acceleration rate of a vehicle include its type, power to weight ratio, etc. Despite this greater significance, most of the past studies on acceleration are based on the data collected from developed countries. The proposed models in these studies include constant, linearly decreasing, polynomial and dual-regime models. With this background, Bokare and Maurya [11] observed the effects of the manual gear transmission mechanism on the acceleration behavior of a car. They found that polynomial models fit the observed acceleration data for the first four gears, while the fifth gear is explained by a linear dual-regime model. However, the scope of this study is limited by the fact that many other types of vehicles are generally observed in developing economies. Other acceleration studies include Kumar and Rao [39] and Dey et al. [19], both of which studied relationships between the acceleration rate and overtaking time on two-lane roads. Thus, future work must try to understand the acceleration behavior of different categories of vehicles under different road and traffic conditions.

Passenger Car Equivalents

The concept of passenger car equivalents (PCE) was introduced in the Highway Capacity Manual 1965, to account for the effects of trucks and buses. PCE, also known as Passenger Car Unit (PCU), was defined in HCM 1965 as “The number of passenger cars displaced in the traffic flow by a truck or a bus, under the prevailing roadway and traffic conditions". Later in HCM 2000, this definition is extended to include the effects of heavy vehicles, in general. Several methods have been proposed to estimate these PCE values using various equivalence criteria. These methods include Walker's method, headway ratio method, density method, simulation based methods and multiple regression methods [30, 38, 81, 82, 87, 90, 92]. However, PCU values depend on various vehicular, traffic stream, geometric and control conditions, all of which are not taken into account in these methods. Studies have shown that the PCE of a vehicle depends on the method of derivation [14, 36]. Al-Kaisy et al. [3] found that the PCE values suggested by HCM are only applicable for free-flow conditions and attempted to derive PCE values for congested conditions. They are, in fact, shown to behave as random variables that generally follow the normal distribution. Moreover, as pointed out by Van Aerde and Yagar [87], the assumption that a single set of PCE values being suitable for capacity, speed, platooning and other types of analysis appears to be incorrect and it is perhaps the main source of discrepancies among the various PCE studies.

It should be clear, from the above discussion, that the studies made in developed economies are solely concerned with the effects of heavy vehicles on the passenger cars. The traffic scenario in developing economies is much more complex, as explained in the introduction. Lane-discipline is a fundamental assumption for the most of the methods discussed above. Hence, those methods cannot be applicable to the mixed traffic, without the necessary modifications. As will be seen in later sections, PCUs are almost exclusively used in capacity and saturation flow studies. Though, because of the complexity in their estimation, some researchers preferred using the traffic composition in their analyses, PCU still remains among the most extensively studied parameters in the developing economies with mixed traffic.

Several researchers have attempted to derive PCUs based on different traffic characteristics. Some of these studies are aimed at studying the effects of specific vehicle types. Rahman and Nakamura [71] attempted to derive PCUs of rickshaws using the average speed reduction in the passenger car caused by their presence for the traffic in Dhaka metropolis, Bangladesh. They showed that these PCU values increased with an increase in their proportion in the traffic and the total volume. Rongviriyapanich and Suppattrakul [75] used time headways between different combinations of cars and two wheelers and calculated PCU values using three different approaches. Data for this study was collected at a mid-block section in Bangkok, Thailand. Traffic in developing economies usually consists of various other types of vehicles in significant proportions. Hence, other studies have used more general methods to estimate the PCU values. Tanaboriboon and Aryal [84] classified the vehicles observed in Thailand into three major types, namely: small, medium and large vehicles and used headway based method advocated by Krammes and Crowley [38] to calculate PCUs, with small sized vehicle as the design vehicle. Arasan and Krishnamurthy [7] studied the effects of varying traffic composition, volume to capacity ratio and road width on PCUs using a simulation model. In this study, PCU of a vehicle is estimated as the ratio of the number of cars that need to replace the subject vehicles in the traffic such that the average speed of cars remains the same. Significant differences are observed with the varying road and traffic conditions. A few other attempts to give modified PCU estimation methods are discussed below.

Modified Density Method

HCM 2000 used density method for the estimation of various PCE values. Tiwari et al. [85] modified this method to be suitable for Indian traffic conditions. They showed that the 85th percentile distribution width of each category of vehicles is a more accurate measure in these conditions than the total width used in the original method. They also gave an adjustment factor to convert passenger cars in heterogeneous traffic into its homogeneous traffic counterpart. This difference may be a result of the intrinsic differences in the driver behavior and road conditions. The basic idea of this method is to compare densities of various traffic entity types at the same speed. The car density is estimated at different speeds of other vehicles using a car density vs. car speed graph. Thus, PCE value of each traffic type is given by:

$$(\mathrm{PCU}_{\mathrm{xi}})_j = \left[\frac{k_{\mathrm{car}}/w_{85\mathrm{car}}}{q_{X_i}|u_{X_i}/w_{85X_i}}\right]_j$$

where for the highway type j, q_{xi} is the flow of traffic entity group X_i in heterogeneous traffic (entities/h) and u_{X_i} is the space mean speed of traffic entity group X_i(km/h). W_{85X_i} is the 85th percentile distribution width (m) for traffic entity group X_i in heterogeneous traffic, and PCU_{X_i} is the passenger car unit for traffic entity group X_i.

Method Based on Areas and Speeds of Vehicles

Chandra and Kumar [16] proposed a new "heuristic" method to estimate the PCE values in the mixed traffic conditions. This method does not have an equivalence criterion to estimate the effects of the other traffic entity types in terms of passenger cars. Instead, it compares the area and speeds of each vehicle type with those of passenger cars. Note that the usage of projected area of a vehicle is a more appropriate indicator in weak lane-disciplined traffic than its length. PCE value of a vehicle type is given by:

$$\mathrm{PCU}_i = \frac{V_c/V_i}{A_c/A_i}$$

where V_c and V_i = mean speeds for cars and type i vehicles, respectively, in the traffic stream; and A_c and A_i = their respective projected rectangular areas on the road.

In addition to its simplicity, no hypothetical scenario of passenger cars only traffic is needed to be considered in this method and it is not necessary to make use of relations based on any equivalence criterion. These advantages are, probably, the reason for its extensive usage in the later studies [55, 56]. This idea is even extended to define motorcycle equivalent factors for the studies in countries where it is more meaningful to take Motorcycle as the design vehicle type [12, 37].

In summary, the notion of a constant PCU for different traffic and road conditions has been proven wrong on several occasions [15, 29]. In fact, explainable trends have been observed in the PCUs with these varying conditions. For example, with an increase in the traffic volume, PCUs calculated in Arasan and Krishnamurthy [7] show increasing and decreasing trends at lower and higher volumes, respectively. Similarly, in Mehar et al. [55], only a decreasing trend is observed with the increase in traffic volume. While the logic of the specific method used is needed to explain these trends, they must be consistent with our intuition that the operating conditions change with the traffic volume. There is no “correct” method to estimate PCUs, but each method helps in understanding the effects of the subject vehicle on traffic from a different perspective [1].

Stream Equivalency Factor: An Alternative Measure to PCU

Given the complexity of the estimation of PCU values, it is natural to look for an alternative measure in the capacity analysis studies. Dhamaniya and Chandra [21] proposed such a measure known as stream equivalency factor (SEF) and denoted by K. It is defined as the ratio of traffic volume in PCU per hour and the volume in vehicles per hour. A regression equation is formulated to estimate this K factor based on the traffic composition and the volume on a road, using a micro-simulation program. Naturally, all the factors influencing the PCU values extend to SEF. However, unlike PCUs, this measure has not been studied for different road and traffic conditions. Hence, to establish its advantage over the PCUs, it is yet to be studied extensively.

Lateral Characteristics

Understanding lateral characteristics is essential to understand the complexity of the mixed traffic, in particular, the effects of weak lane-discipline. However, only a few studies have been made in this direction in the past. Most of the studies made in developed economies are limited to analyzing the criteria for performing an overtaking maneuver. Similarly, in the mixed traffic studies, gap acceptance functions are used in the micro-simulation models. Though, these functions have been successful in bringing the absence of lane-discipline into the model, they do not have a strong empirical basis and are primarily heuristic [6, 53, 80]. Hence, more observational studies are needed for a clear understanding of the vehicle dynamics. In this section, only the empirical studies in this respect are reviewed and the models are delegated to the Sect. on “Modeling”.

Safe driving is the primary concern of any vehicle driver and is achieved by avoiding risky situations by observing the surrounding vehicle and road conditions and adjusting to them appropriately. Therefore, the non-collision constraints and the minimum longitudinal gap requirements formed the basis for many homogeneous traffic flow models like car-following models. Because of the weak lane-discipline, it becomes necessary to give an equal importance to the lateral gap requirements in the mixed traffic. As with the longitudinal gaps, the minimum required lateral gap is expected to increase with the speeds of the vehicles. Incidentally, several past studies have proven this intuition to be right and indicated a linear relationship between them, along with the existence of minimum and maximum clearance values, at different speed levels [31]. Thus, the clearances at any other speeds can be calculated using the linear interpolation method. The total lateral clearance is then approximated as the sum of the clearances of individual vehicles, estimated based on their types and speeds independently [6]. The clearance thresholds used in these studies are given in Table 2. Singh [79] developed a relation between the lateral gap and speeds of the interacting vehicles. The study also estimated the minimum and maximum clearance values on two lane roads for different combinations of vehicle types. Mallikarjuna [47] observed that the average gap maintained by the vehicles decreased with an increase in area occupancy. This observation should be intuitive, as the speeds of the vehicles are reduced with increasing area occupancy, which in turn, affect the lateral gaps. Some recent studies have made use of the technological advancements in collecting the data. Mallikarjuna et al. [50] used an image processing software called TRAZER, to extract the required data from the video. It is observed that lateral gaps

Table 2 Transverse clearance thresholds for different categories of vehicles [64]

Type of vehicle	Minimum clearance at zero speed (m)	Maximum clearance at 60 kph speed (m)
Bus	0.4	1.0
Truck	0.4	1.0
Light commercial vehicle	0.3	0.7
Car	0.3	0.7
Auto-rickshaw	0.2	0.7
Motorized two-wheelers	0.1	0.7
Bicycle	0.1	0.5[a]

[a] Maximum clearance at 20 kph

maintained by more or less similar speeds can be approximated with a normal distribution, while those moving at different speeds, with a lognormal distribution. Mahapatra and Maurya [44] used equipment V-Box for collecting the data and investigated the lateral accelerations and yaw rates of three different types of vehicles. They found significant differences in their values and the relationships with longitudinal speed for different vehicles. Unlike lateral gaps, no further studies are made on the lateral accelerations and yaw rates. Future research should focus on understanding these characteristics and their importance in accident and congestion analyses.

Capacity and Level of Service (LOS)

Highway capacity is defined as the number of vehicles that can reasonably be expected to traverse a point of the road section in unit time, under the prevailing road, traffic and control conditions. Knowledge of capacity is essential for a traffic engineer for the purposes of design, planning and operational analyses of the road sections. Realizing its importance, many researchers have proposed various direct and indirect empirical methods for its estimation [59]. While direct empirical methods require the observation of various traffic characteristics like headways, volumes, speeds and densities from real traffic data, indirect empirical methods require the same but from a simulation model. The guidelines for capacity estimation provided by various agencies, including TRB (HCM) and Indian Roads Congress (IRC), are based on the indirect empirical methods. Speed–flow relationships are constructed using these observations, leading to the estimation of capacity. Similarly, level of service (LOS) is a qualitative measure used to understand the perception of quality of service by the drivers at different flow levels. This concept was first introduced in HCM 1965, along with the concept of PCU and formed the basis for many PCU estimation methods. HCM 2010 provides methodologies for the calculation of LOS for different road facilities. LOS is designated using letters A–F, with F indicating congested flow. Density is used as the primary classification criterion for many of the uninterrupted flow facilities, albeit the specific values used are different. The methodologies also make use of speed–flow curves and adjustment factors for heavy vehicles, etc. Table 3 shows the LOS criteria for basic freeway segments.

Table 3 LOS criteria for basic freeway segments (HCM 2010) [86]

LOS	Density (pc/mi/ln)
A	≤11
B	>11–18
C	>18–26
D	>26–35
E	>35–45
F	>45 (demand exceeds capacity)

There exist two main differences in the capacities of the road sections with the homogeneous traffic and the mixed traffic:

1. The estimation procedure in the latter case has a rather significant task of converting the different types of vehicles observed on the road section into the equivalent units of a single design vehicle type. Depending on the predominant vehicle type in each case, passenger car equivalents (PCU) or motorcycle equivalents (MCE) have previously been used for this purpose. While the homogeneous traffic may also consist of a small proportion of heavy vehicles, a simple PCU method is sufficient for their conversion into passenger cars.
2. While the capacity in the former traffic scenario is estimated per lane, the entire road section as a whole is needed to be considered in the latter case, as a clear distinction of lanes is absent in this traffic. This is a direct result of the weak lane-discipline of the vehicles observed in the latter case.

These additional difficulties pose a greater challenge to the capacity estimation in the developing economies. Several researchers have attempted to accomplish this task for various road and traffic conditions. Speed–flow relationships were constructed and the apex of that graph i.e., the highest volume allowed on that road in terms of the equivalent units is taken as the capacity of that road section for those specific conditions. However, these studies differed in their methods of estimating equivalent vehicle units (PCE/MCE) and in whether the data is actually collected at the road sections or simulated using a microscopic model. As the former way is rather tedious and infeasible at times, many researchers preferred the latter to observe the effects of different road and traffic conditions.

Early researchers observed that the capacity standards adopted in developed economies are not applicable for mixed traffic conditions and pointed out the necessity to develop different standards for such conditions [73, 78]. Chandra [17] collected data from 40 different sections of two-lane roads from different parts of India and attempted to observe the effects of various influencing parameters like gradient, lane width, shoulder width, traffic composition, directional split, slow moving vehicles and pavement surface conditions, on capacity of two-lane roads. These effects are evaluated and multiplicative adjustment factors are given for deviations from the base conditions. Chandra and Kumar [16] developed a second-degree equation between capacity and the total width of carriage way using the data collected from ten different two-lane road sections. Similarly, simulated data was used by several researchers to derive capacities for different road widths and traffic compositions [6, 69, 88]; Mehar et al. [55]. Multi-regime models were most commonly used to fit the speed–flow relationships with this data [69, 88]. Cao and Sano [12] modified the method proposed by Chandra and Kumar [16] to calculate MCEs for different vehicle types. They used field data collected from 12 approaches in Hanoi, Vietnam to evaluate the fundamental relationships between speed, flow and density and observed the effect of number of lanes on capacity.

As can be seen from the above review, there seem to be a general consensus in the capacity estimation procedure, other than with the equivalent unit part. However, that is not the case with the LOS studies. Although both capacity and LOS are related concepts, the latter is a qualitative measure and is aimed at capturing the perceptions of users about their surrounding conditions. Maitra et al. [46] attempted to develop a balanced congestion measure incorporating operational (delay, user cost, etc.) and volume (capacity, volume) characteristics. They proposed ten levels of service, nine in the stable flow zone as A–E and one unstable as F, based on that measure as the criteria. Similarly, Taweesilp et al. [83] used platoon characteristics to measure LOS in four levels, namely: free-flow condition, partial-constraint condition, constraint condition and congested condition. Rahman et al. [72] classified levels of service into six categories based on passing-overtaking maneuvers. However, this model is applicable only for traffic stream with relatively high proportion of rickshaws. Marwah and Singh [52] proposed four levels of service based on journey speeds of the cars and motorized two-wheelers, concentration and road occupancy of the traffic stream. This wide variation in the measuring criteria used is not surprising, given the complexity of the traffic stream and the broadness of the LOS definition. Similar problem was seen before with the equivalent vehicle unit (PCE/MCE) estimation methods. Therefore, further work is needed to compare the potential criteria of LOS and identify their suitability for the specific applications.

Saturation Flow and Delay Studies at Signalized Intersections

Saturation flow is a very similar concept to the capacity, except that it is measured during the green time at signalized intersection. It is defined as the maximum number of equivalent vehicle units (PCE/MCE) that could cross the stop line, if the signal remained green all the time. And the capacity of an intersection approach is obtained by multiplying this quantity to the ratio of green time to the total time of the signal cycle. Along with the road geometric, environmental and traffic stream factors affecting the capacity, saturation flow is also affected by the intersection specific characteristics like the proportion of turning movements at the intersection. Due care must be given to the start-up lost time in the saturation flow analyses, which is a result of the initial vehicle drivers' reaction and acceleration times. During the queue discharge process after the start of green time, a saturated condition is reached after the first few vehicles. Headways of these vehicles are greater than those of the subsequent vehicles. This initial delay was accounted for in the estimation of saturation flow in the following studies. Hossain [29] developed a regression model for the saturation flow in the units of vehicles per hour, using a simulation model called MIXINET. The influence variables considered in this equation are road width, turning proportion, percentages of heavy and non-motorized vehicles. Often, saturation flow is estimated as the reciprocal of the average headway at the intersections and is given in the units of PCUs per hour [20, 60]. Furthermore, Arasan and Jagadeesh [5] adopted a probabilistic approach to estimate the saturation flow and the delay caused to traffic at signalized intersections. Webster's method [89] is modified to incorporate the interaction between different vehicle types through their inter-correlation. A few attempts were made to study the effects of the motorcycles, which have a significant share in traffic in developing economies [4, 60]. Vehicle creeping is an important phenomenon observed, particularly, at signalized intersections. Powell [70], though not describing the motorcycle behavior in detail, modified a first-order macroscopic model to predict the number of motorcycles, which set off from the front of the queue before the end of the first 6 s of effective green time. A thorough understanding of the effects of "vehicle creeping" is still lacking in the literature.

Delay experienced by the vehicles at the signalized intersections is often studied along with the saturation flow. It is an important performance evaluation measure and is critical in analyzing and designing the signal timings.

Webster [89] developed a delay model based on queuing theory, which laid the foundation for the later studies. Most of these studies retained its basic assumptions in the formulation of their models and proposed modifications to the original Webster's model addressing its limitations. However, these models cannot be used in developing economies without significant modifications. Several researchers have proposed modifications to the Webster's model to account for the variability in mixed traffic. Arasan and Jagadeesh [5] attempted to do this by incorporating the interaction between different types of vehicles through their intercorrelation. Minh et al. [62] developed an analytical methodology for the estimation of mean and variance of delay. They found that the output of the proposed methodology is closer to the observed data than that of the conventional Webster's model. Recent studies have further attempted to optimize the signal timings so as to minimize the intersection delays [65, 76].

Modeling

Simulation techniques have proven to be an indispensable tool in traffic engineering, along with many other disciplines. They make it possible to observe the effects of proposed transport policies, road designs and signal controls, and thus, helping the transport planners and traffic engineers in decision making. They even provide a faster and economical alternative for the empirical data collection. Realizing their importance, researchers have developed a myriad of simulation models, both in developed and developing economies i.e., for homogeneous and mixed traffic. However, most of these models, especially those for mixed traffic, make simplified assumptions about the road and traffic conditions, rendering their applicability limited. In addition, for homogeneous traffic, considerable research has been done in developing models with different levels of detail, broadly classified as microscopic, mesoscopic and macroscopic, whereas for mixed traffic, much of the attention is given to the development of microscopic models and very few attempts have been made to develop macroscopic ones. In this section, a discussion on the general structure of the microscopic models for mixed traffic is given, followed by a detailed review. And a brief review of the research in macroscopic models is also given at the end.

Sub-Models of a Micro-Simulation Model

Both the longitudinal and the lateral controls are equally important in the modeling of mixed traffic and a realistic simulation model must be able to reproduce the absence of lane-discipline. Such a realistic representation requires a detailed knowledge of the various aspects of the field conditions. The studies on the individual characteristics reviewed in the previous sections are helpful in characterizing and modeling these different aspects. As will be reviewed later, depending on the intended application and the desired level of detail, not all these characteristics were considered in developing the previous micro-simulation models. A comprehensive micro-simulation model is made up of a number of sub-models defining these characteristics. Given below is the list of the sub-models/components of the simulation model, which form the groundwork for the implementation of vehicle movement logic, grouped based on the nature of their contribution:

1. Roadway and signal control design:
   - Number of lanes
   - Lane width
   - Type of roadway
   - Shoulder conditions
   - Intersection geometry
   - Allowed movements
   - Signal design
   - Priority rules
   - Other roadway features like gradient, curves, road surface condition, etc.
2. Traffic generation:
   - Headway (or) arrival time generation model
   - Vehicle type assignment model
   - Speed assignment model
   - Turning proportions at a junction
3. Vehicle characteristics:
   - Length
   - Width
   - Projected area on the ground
   - Speed distribution model
   - Acceleration vs. speed relation
   - Deceleration vs. speed relation
   - Yaw rate vs. speed relation
4. Operational characteristics:
   - Drivers' perception-reaction time
   - Longitudinal headway requirements
   - Lateral clearance requirements
   - Acceptable gap for a merging maneuver at an intersection

General Outline of the Micro-Simulation Model

The primary objective of a micro-simulation model is to model the interactions of a given vehicle with its surrounding road and traffic conditions. More precisely, it is to model how each driver perceives his/her surrounding conditions and maneuvers the vehicle accordingly. In any given scenario, the actions/decisions taken by the drivers can be hypothesized to be motivated by two factors [13]:

(a) Their concern for safety
(b) Their urge to reach the destination as quickly as possible

The complexity in modeling the mixed traffic lies in formalizing these two concepts i.e., safety and urgency, in order to predict the behavior of different vehicle-driver combinations interacting on a road section. While this description suffices for models of only uninterrupted traffic streams, additional considerations must be given to the problems faced at other road network components like signalized and unsignalized intersections. Overall, a simulation process can be divided into various modules, including the ones that do the preparatory work for the simulation (1) and the post-simulation analyses (6, 7). Seven such modules are identified here and are given below:

1. Input of the relevant road network features
2. Traffic generation
3. Vehicle placement
4. Vehicle movement at a mid-block section
5. Additional movement logics at other road network components
6. Animation of the on-going simulation
7. Data output and further analyses

The following subsections describe these seven modules briefly.

1. Input of the relevant road network features:

This module models the physical and control aspects of the real world. It includes the geometric design of the road elements like links and intersections, and the traffic signal design at those intersections. Other regulations like the allowable movements on each road link must be incorporated at this stage. If needed, potholes and other obstructions, which are common in developing economies, can also be included in this module.

2. Traffic generation:

The arrivals of the vehicles and their attributes in any given road section are inherently stochastic in nature. Random number streams are generated from different probability distributions to model vehicle generation, identification of the vehicle type and the assignment of the free speed. The observed flow rate and traffic composition data are used here. Commonly used headway distributions include negative exponential distribution, shifted exponential distribution, etc. Free speeds of each vehicle type are usually assumed to follow normal distribution. In the case of intersections, information regarding the turning proportions may also be used in this module.

3. Vehicle placement:

After the generation of a vehicle, a safe transverse position must be chosen for its placement at the start of the simulation stretch. It should be seen that enough longitudinal and lateral clearances are available for that vehicle with its surrounding environment. Also, the drivers of different vehicle types may prefer any particular side of the road because of the safety concerns or for the advantage of easier maneuvers. This is a very common observation in the mixed traffic conditions. For instance, in countries like India, where the "keep left" traffic rule is followed, heavy vehicles tend to move on the right-most of the permitted lanes, exemplifying risk-aversion behavior of the drivers. Whereas, smaller vehicles like two-wheelers are mostly observed on the left-most lane or even on the shoulders. These observations can be made use of in this module. At higher traffic volumes, the possibility of having to generate more than one vehicle in the same time step must also be allowed. By default, the desired speed should be assigned to the subject vehicle during its placement. However, if the available clearances are inadequate to avoid collisions in the next time step, a car-following scenario shall be assumed and the speed of the slowest leading vehicle can be assigned to the subject vehicle (Note that having more than one leading vehicles is possible in mixed weak lane-disciplined traffic). If the clearances are still not adequate to allow this, the entry of the vehicle is awaited until the next time step.

4. Vehicle movement at a mid-block section:

This module deals with the updation of the longitudinal and lateral positions of the vehicle and forms the crux of the micro-simulation model. In general, two of the vehicle's attributes are chosen to represent its two-dimensional movement and to be updated in each time step. For example, Chakroborty et al. [13] developed acceleration and steering models to update longitudinal and lateral positions, respectively, whereas Arasan and Koshy [6] updated the longitudinal speed and lateral position, instead. Moreover, the concepts of "safety" and "urgency" act as the guiding factors of the development of the logic. The surrounding environment of a vehicle i.e., the space headways and speeds of the leading vehicles and distances from other obstacles are used in formulating the updation models. The possibility of overtaking slow moving vehicles must be explored, while maintaining safe lateral and longitudinal clearances with the surroundings objects. Thus, a tendency to fill the available gaps (ignoring the lane markings) is observed among the drivers. The conventional car-following behavior can, at best, be a special case of this "gap-filling" behavior. Additional constraints like the speed of the vehicles not exceeding their desired speed, the acceleration/deceleration limits at different speeds must be duly considered. While these basic ideas are retained in the micro-simulation models proposed by different researchers, the framework in which these ideas are implemented varies. As will be seen later, these frameworks include cellular automata [48], a force field analogy [13], identifying different mechanisms of vehicle movement [58], etc.

5. Additional movement logics at other road network components:

While the drivers are still motivated by the factors of safety and urgency, the logics presented in this module are more specific to the road network component at hand. For instance, at a signalized intersection, the responses of the vehicle drivers to the traffic signal changes collectively result in the formation and dissipation of queues. Similarly, at an unsignalized intersection, the vehicles in the front of the queue look for an acceptable gap to move in the direction of their choice. Researchers have attempted to incorporate such observations at signalized and unsignalized intersections, traffic circles, priority type junctions, etc. The most important (or) the most common one among these observations i.e., the gap acceptance behavior is explained here. The vehicle drivers look for the availability of enough gaps in different situations to make maneuvers like merging and crossing. Obviously, the average gap requirements of different vehicle types vary. In addition, because of the weak lane-discipline observed in mixed traffic, it is even more difficult for the drivers to perceive the time gap with the conflicting vehicle accurately, resulting in its stochasticity. Log-normal distribution is found to be fit for the time gap data collected at a junction in Dhaka [26]. In a given time step, the vehicle enters the junction, if the available gap is greater than the critical gap. Otherwise, it is awaited until the next opportunity arises. Similar mechanisms/logics are used to model the other observed phenomena in a road network.

6. Animation of the on-going simulation:

Strictly speaking, this module is not "necessary" for the development and the usage of a micro-simulation model. However, the animation of the on-going simulation makes it easier for a modeler to understand how precisely the simulation model is able to replicate the actual traffic situation. In fact, any need for modifications in the model can be easily identified with this visual tool. Moreover, a traffic engineer can also use this animation tool to get an initial idea of the traffic condition in a road network and make decisions on the further analyses.

7. Data output and further analyses:

Simulation offers a faster and economical way of collecting the data under different road and traffic conditions. The purpose of this module is to provide the output of the simulation in the form of details pertaining to different road sections like flows, spot speeds and area occupancies, and to individual vehicles like trajectories, travel times, etc. Portions of the road section at the start and exit ends of the simulation stretch are excluded from consideration, to avoid the transient states of traffic at these locations due to the generation and deletion of vehicles, respectively. Thus, the data from the valid portion of the simulation stretch in the middle can be used to conduct further statistical analyses (or) to understand the impact of various traffic control strategies by the traffic engineers.

Review of the Previous Micro-Simulation Models

While the basic structure of all the micro-simulation models remains the same as discussed above, various models proposed in the past differ in its implementation, in particular:

(a) The representation of road and traffic elements.
(b) The framework in which the vehicle interaction is implemented.
(c) The targeted road network components. Ex: mid-block, intersections, etc.
(d) Captured level of detail of the vehicle maneuvers.

Table 4 presents the details of a few selected models to show the variety in the modeling strategies. Car following theory (reviewed by May [54]) developed for homogeneous traffic conditions formed the groundwork for most of the proposed models. As can be observed from the descriptions in the table, there is a lack of attention to the lateral control of the vehicles and the longitudinal control primarily uses the principles of homogeneous car-following models. However, as noted above, it is more appropriate to describe the driver behavior as "gap-filling", in which the car-following maneuvers can only be considered a special case. Incorporating this behavior requires giving explicit consideration to the lateral characteristics like steering angle, which was done by only a few researchers in the past [13, 23]. It must also be noted that lower speeds are observed with the vehicles having less lateral clearances with their surroundings. This can be attributed to the "psychological" overlapping perceived by the vehicle drivers [23], but is rarely seen incorporated in the models. These deficiencies can only be resolved with more empirical studies to develop insights into the lateral characteristics in the mixed traffic. Another prominent type of models developed for mixed traffic are "Cellular

Table 4 A comparison of the previous micro-simulation models

Model name	Framework	Longitudinal movement	Lateral movement	Type(s) of the road component	Limitations	Other remarks
MIXINET [27–29]	Co-ordinate based system for vehicle location	Adopted CARSIM, a non-collision based car-following model (Benekohal and Treiterer [9])	Check for longitudinal spacing using a non-collision constraint with the new follower. Requirements of lateral clearance unclear	Divided arterials, traffic circles, signalized intersections	Lateral maneuvers not explicitly modeled	A gap acceptance model is used at the intersections. Critical gaps are randomly generated for the vehicles from a log-normal distribution [26]
HETEROSIM [6]	Co-ordinate based system for vehicle location	If no slow moving vehicle in front, accelerated to the desired speed. Else, if overtaking also not possible, decelerated to the leading vehicle's speed	Check for minimum lateral clearance, which is given as the sum of individual vehicles' requirements at their respective speeds	Divided arterials	Lateral maneuvers not explicitly modeled	Lateral clearance requirements assumed to be linearly related to the vehicle speeds and are adopted from Nagaraj et al. [64]
Driver behavior based model [13]	Force field analogy used. Potential functions are given for different types of obstacles	An acceleration response model using current speed of the vehicle and the potential at its location	A steering response model also using the current orientation and the potential at the vehicle location	Divided and undivided roads	High computational resource requirements because of the high level of detail	Realistic vehicle maneuvers are predicted by the model in different driving scenarios
Staggered car-following model [23]	Modified (Gipps' [22]) model. Cars-only traffic with weak lane-discipline considered	Speed determined by the most restrictive of that calculated using the following criteria: (I) Free flow speed (II) Basic car-following (Gipps) model (III) Maximum escape speed (MES) (IV) Adequate veer time to avoid rear-end collision	Lateral discomfort accounted for in the calculation of the longitudinal speed (III and IV criteria)	Divided roads	Only one type of vehicle is considered	Metkari et al. [57] extended this model for multiple types of vehicles Unlike most of the earlier models, the formulae for the speed calculation are formally derived for weak lane-disciplined traffic
A basic cellular automata model [48]	Road section divided into cells of constant size	Updation rules of acceleration/deceleration are given to based on available time headway	Two criteria for lateral movement: (I) Incentive for the movement (II) Safety criteria Checks for available longitudinal and lateral spacings are performed under these two criteria	Divided roads	Vehicle sizes, speeds, etc. can only be given in multiples of the cell size Loss of detail with coarser cell sizes and more computational intensive with smaller sizes	Pal and Mallikarjuna [68] studied the relation between cell width and area occupancy on the road section
A two-dimensional car following model (Xie et al. [93])	Based on an existing two-dimensional optimum velocity model for pedestrian flow (Nakayama et al. [67]) Two types of vehicles namely, motorized and non-motorized vehicles are considered	Acceleration/deceleration model using the velocity differences and the interactions with the surrounding vehicles and the boundaries		Unsignalized intersections	The differences between the various vehicle types observed in developing countries not explicitly incorporated	Numerical simulations are carried out predicts the realistic phenomena of alternative passing of the two groups of vehicles at the intersection

Automata" models. In these models, the road section is divided into rectangular cells of predetermined length and widths, whereas the vehicles are represented by filling a cluster of these cells, based on the actual vehicle dimensions. These models can be seen as the discretized versions of the car-following models described above. The vehicle speeds, acceleration/decelerations, sizes, gap requirements, etc. are discretized, with the same underlying criteria as before for the longitudinal and lateral movements, in the form of updation rules in each time step [42, 48, 57]. The advantages of this type of models include lesser computational effort and ease of implementation, while the disadvantages include loss of detail because of the discretization. More importantly, the constant sizes of the cells adopted by most models make it difficult to account for the variability in gap requirements with vehicle speeds. A special mention should be given to the micro-simulation software VISSIM, which is extensively used in various mixed traffic studies. However, this software uses a psycho-physical car-following model developed by Wiedemann and Reiter [91]. Though, this model is developed for homogeneous traffic conditions, its wide popularity in the research community can be attributed to its accessibility. Moreover, it is, in fact, shown to replicate the actual mixed traffic scenario reasonably well. Another important aspect of the modeling studies is the calibration of the model parameters. Mathew and Radhakrishnan [51] gave a methodology for calibrating model parameters for the mixed traffic conditions at a signalized intersection. They used genetic algorithm techniques to minimize the field and simulated delays and demonstrated their methodology using VISSIM. Similarly, Kanagaraj et al. [33] evaluated four car-following models namely, (1) Gipps model, (2) Intelligent Driver model, (3) Krauss model and (4) Das and Asundi model, appropriately adopted for mixed traffic conditions. They used various performance measures like errors in hourly stream speeds and class-wise speeds, critical parameters and mean absolute percentage error (MAPE) for speed and density values, obtained at 1 min intervals.

Area Occupancy

Before entering into the topic of macroscopic modeling, it is worthwhile to introduce a new traffic measure essentially developed to cater the needs of mixed traffic. This measure replaces one of the fundamental traffic characteristics i.e., 'density', whose conventional definition is as follows: the number of vehicles occupying a unit length of road section at an instantaneous time. In the mixed traffic conditions, where the vehicles widely differ in their static and dynamic characteristics, only giving the total number of vehicles is meaningless and it must be accompanied by the traffic composition. Therefore, the researchers have used the concept of occupancy instead, where the projected area of the each vehicle type on the roads is used as the basis. It can be formally defined as follows: the proportion of time the set of observed vehicles occupy the given stretch of the roadway and is expressed as:

$$Area\ Occupancy = \frac{\sum t_i a_i}{\mathrm{TA}}$$

where t_i = time during which a stretch of the roadway is occupied by vehicle i in s (occupancy time); a_i = projected area of the vehicle i on the road in m^2; A = area of the entire road stretch under observation in m^2 and T = total observation period in s.

Though the concept of area occupancy was formally introduced recently by Mallikarjuna and Rao [49] and Arasan and Dhivya [8], the idea has earlier been adopted by researchers under a disguise [35, 66]. This replacement is a significant step forward in the research of mixed traffic. However, it is doubtful how well this measure could account for the differences in dynamic characteristics i.e., speeds and accelerations of the vehicle types. While the time variable depends on the speed of the vehicle under consideration, it also depends on the times of entrance and exit of the vehicle, casting a doubt on its reliability. Moreover, this variable can be ignored entirely, when the area occupancy is calculated at an instantaneous time, in which case, the measure is completely independent of any dynamic characteristics of the vehicles. Hence, no conclusive statement can be made at this point without an understanding of the effects of traffic composition on area occupancy, which forms a scope for the future research.

Macroscopic Modeling of Mixed Traffic

Unlike microscopic models, where the objective is to model the individual vehicle maneuvers, macroscopic models aggregate the entire traffic stream on the subject road section, in terms of the traffic flow characteristics like flow, density and mean speeds of the traffic stream. Lighthill and Whitham [43] and Richards [74] independently proposed the first-order traffic flow model, using the analogy between vehicular and fluid flows. Later researchers have proposed higher order, multi-class and multi-lane extensions of this model in an attempt to explain various observed traffic phenomena. Interested readers can refer to Hoogendoorn and Bovy [25], Mohan and Ramadurai [63] for a detailed review of the evolution of these models. For the purposes of this review, it suffices to say that the three basic equations for all these models are the conservation of vehicles equation, the fundamental equation of traffic flow and the speed–density relationship. Different models differ in their definition of the speed–density relationship and multiple sets of these equations are given in the multi-class and multi-lane extensions. Bhavathrathan and Mallikarjuna [10] gives a review of these extensions of LWR models. However, these extensions do not incorporate the characteristic features of the mixed traffic i.e., different types of vehicles using the same road stretch and the absence of lane-discipline. The first attempt at proposing a continuum model explicitly considering the mixed traffic conditions was by Nair et al. [66], where the mixed traffic stream is observed to define a porous medium and each vehicle trying to move downstream through the available pores. Naturally, the pore requirements of each vehicle class depend on its size. Along with the usual traffic state variables for flow, density and speed, a new function called "Pore distribution function" is defined in the form of a probability distribution function to implement the porous medium approach in the framework of LWR model. An approximate finite difference scheme is also proposed to solve the resulting system of partial differential equations. This model succeeds in explaining a phenomenon observed in mixed traffic called 'creeping', in which the smaller vehicles moves through the gaps to the front of the queue because of their easier maneuverability. However, the drawbacks of this model include simplistic and deterministic descriptions of equilibrium speed–density relation, critical pore size, etc. Also, this model has not been calibrated and validated using real data. Another notable model was proposed by Mohan and Ramadurai [63], where they extended an existing second-order model, Aw-Rascle model to the mixed traffic conditions. Each vehicle class is given a separate set of PDEs and the 'density' term in the original model is replaced by 'area occupancy'. The resulting hyperbolic system of equations is calibrated and validated using real traffic data, and is found to better capture the traffic conditions, when compared to an earlier multi-class extension of LWR model. However, unlike that of homogeneous traffic, there is no strong empirical (or) mathematical foundation for the development of the continuum traffic flow models for mixed traffic. Moreover, most of the higher order models are derived from the car-following models, which are essentially developed for homogeneous traffic. Further, there is no clear physical interpretation for some terms in higher-order models, which might hinder getting better insights into the mixed traffic phenomena. Thus, the need for the research at a more foundational level is clear from the above review.

Summary and Conclusions

This article summarizes the studies on various mixed traffic characteristics in developing economies. However, the studies addressing the problems of any particular country but not relevant in others are not included. It can be seen that the ideas and concepts of homogeneous traffic studies have been used in the studies of many mixed traffic studies. Only a brief overview of the former's studies is given here, with directions to the relevant publications for the interested readers.

The objective of this article is three-fold: to provide a comprehensive review of the studies on mixed traffic in developing economies, to identify the limitations and gaps in the current understanding of the traffic characteristics and to provide a background and guidelines for the researchers in planning their future studies. All the reviewed studies have been organized in six sections, namely vehicle characteristics, passenger car equivalents, lateral characteristics, capacity and level of service, saturation flow and delay studies at the signalized intersections and modeling. Except the final section on 'modeling', each of the sections presents a review of the previous studies on that topic, under a few subsections, as needed. It is generally observed that the concepts of homogeneous traffic have formed the basis for many of these studies. The shortcomings of those concepts in mixed traffic conditions have been emphasized, along with other gaps in the knowledge of those traffic characteristics and thus, identifying the possibilities of the future research. Finally, a general outline of a micro-simulation model for mixed traffic is described, along with a review of the previous models. A comparison of various micro-simulation models is presented and a lack of attention given to the lateral vehicle maneuvers is identified in the review. Also, a brief review of the macroscopic modeling, which is still in its nascent stages for mixed traffic, is provided.

Despite the initial adoption of the ideas from homogeneous traffic studies, the modifications in the later studies have given satisfactory results in some of the reviewed areas. However, this evolution has been inadequate in the other areas, resulting in the gaps/limitations in their understanding. With the understanding of these limitations, the authors identified the following as high-priority areas for the future research.

Firstly, a lack of empirical knowledge, particularly of the vehicle specific characteristics like lateral clearance and acceleration, has been observed, at various points in this review. An understanding of these characteristics is essential in the formulation of a simulation model that can reproduce the realistic vehicle maneuvers. Further research in this direction is needed to provide the necessary foundation for the modeling studies.

Secondly, future research on micro-simulation models, particularly those based on car-following models, must focus on developing more realistic models/logics for the lateral movement. The lack of empirical research pointed out above is partly responsible for the inadequacy of the current models. However, the shift from car-following to gap-filling behavior can be brought into the simulation model only with further improvements in these logics.

And finally, given its history and development in developed economies, it is surprising that the studies on macroscopic modeling have been virtually non-existent, until recently. No significant advancements have been made in this topic, other than the replacement of density with area occupancy, pointing out the need for research at a fundamental level.

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