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Autonomous Intelligent Systems

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Behavioral models of drivers in developing countries with an agent-based perspective: a literature review

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Abstract

The traffic in developing countries presents its own specificity, notably due to the heterogeneous traffic and a weak-lane discipline. This leads to differences in driver behavior between these countries and developed countries. Knowing that the analysis of the drivers from developed countries leads the design of the majority of driver models, it is not surprising that the simulations performed using these models do not match the field data of the developing countries. This article presents a systematic review of the literature on modeling driving behaviors in the context of developing countries. The study focuses on the microsimulation approaches, and specifically on the multiagent paradigm, that are considered suitable for reproducing driving behaviors with accuracy. The major contributions from the recent literature are analyzed. Three major scientific challenges and related minor research directions are described.

Keywords: Driver behavior, Developing country, Microsimulation, Multiagent systems, Systematic literature review method

1 Introduction

Urbanization is on the rise in developing countries, which are often characterized by their low Human Development Index and trends in nonindustrialized infrastructure [1, 2]. Despite efforts to stimulate economic development, many cities in developing countries face traffic gridlock and struggle to build enough road infrastructure to meet demand [3–5]. Mobility and accessibility are declining in these cities, even as they become more complex [6]. Even if the transportation sector is critical for economic development, informal rules and regulations that can be used in developing countries often make it difficult for road users. Therefore, they face specific challenges [1, 7] in the implementation of mobility and traffic systems. Most urban communities in developing countries have developed without mechanized vehicles and narrow streets without sidewalks. This land use design works well for societies that rely on nonmechanized transportation. However, the growing number of cars is putting pressure on infrastructure, particularly in areas where different types of vehicle share the same roadway. Many cities face challenges related to road safety, such as Delhi, where pedestrians, carts, and vehicles share the same space. Some cities have coped better, such as Shanghai, which has built separate paths for bicycles, slow bikes, and pedestrians. However, there are significant differences in the way vehicles are used and designed in different countries [6]. For example, minivans in South Africa are used for public transportation, although they were not designed for that purpose, and are often overloaded. Traffic patterns in developing countries also generally involve poor lane discipline and heterogeneous traffic, leading to complex interactions between different types of vehicle. In this global context, there has been growing interest in studying driving behav-

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ior in developing countries. In fact, road traffic accidents are the leading cause of death and disability among young people aged 15 to 29 years and among the top three causes of mortality among those aged 15 to 44 years [8]. Human factors, such as driver behavior, contribute to road traffic accidents in many African countries, including Morocco, Algeria, Libya, and Sudan [9–16].

In this situation, simulation is a tool that enables one to reproduce and test driver's behavior and to notice their belongings, without applying them in a genuine rush-hour gridlock environment. Agent-based simulation (ABS) is considered an appropriate paradigm for modeling and simulated traffic systems at the microscopic level [17–20]. An agent is characterized as an autonomous entity located in some environment and equipped with the ability to coordinate with other agents to achieve its objectives [21, 22]. ABS reproduces the global behavior of systems from the definition of local behaviors and their interactions in the environment. ABS involves autonomous agents that interact with each other and the environment to achieve their objectives [21, 22]. It can replicate the behavior of the global system by defining local behaviors and their interactions in the environment.

However, most of the existing models (ABS or not) of longitudinal and lateral driver behavior are generally designed for developed countries. They do not adequately capture integrated driving behavior in developing countries [23]. To determine the maturity of the research for modeling the driving behavior in developing countries, a survey should be carried out. Consequently, the objective of this study is two-fold:

1) *Conduct a systematic review of the literature* (SLR) addressing various driving behavior models in developing countries. This SLR means to recognize the main exploration questions, investigate the writing, and outline key difficulties and investigation headings.
2) Outline and discuss *research directions* with suitable suggestions of driving behaviors that are feasible for a developing country.

This article is structured as follows. Section 2 states and defines the SLR methodology adapted from [24, 25]. Section 3 details the analysis and results of the SLR. Based on these results. Section 4 identifies the main research directions. Section 5 discusses related work. Section 6 concludes this article.

2 Review methodology

SLR is a popular and efficient strategy for exploring science fields. According to Kitchenham and Charters [26], SLR is a type of secondary investigation that systematically identifies, analyzes and interprets all available evidence related to a specific research question in an unbiased and partially replaceable manner. This study focuses on investigating different models of driving behavior through literature articles to provide recommendations for modeling driving behavior in ABS. The objective of SLR is to summarize current evidence on widely used technology, identify research gaps, and provide a foundation for new research initiatives [24]. To achieve these objectives, the precise literature uses suitable methods to combine SLRs in transportation and computer science [24, 25], ensuring rigor, fairness and reproducibility. Figure 1 shows the review process.

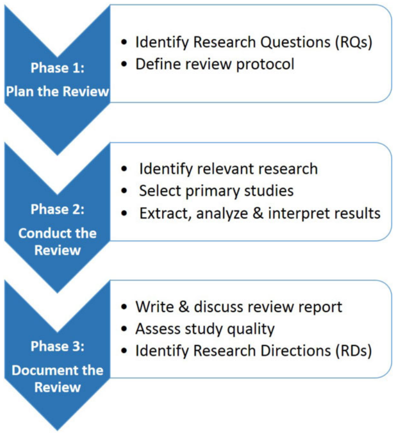

Figure 1 Systematic literature review process, from Mualla et al. [27], adapted from Brereton et al. [28], Galster et al. [29]

2.1 Key research questions

The research study follows the goal question measure (GQM) proposed by [25] to identify key questions related to driving behavior in developing countries. The main challenge is to increase mobility for a large part of the population at reasonable cost without creating environmental problems. Researchers have applied mobility models that were initially designed in the context of developed countries. However, the modeling assumptions used in these models are not relevant to developing countries. For example, the notion of an emerging road was not always supported by these models. It corresponds to roads that appear dynamically depending on the density of vehicles, bikes, and pedestrians present in the area. In other words, traffic flow is not restricted to road infrastructure, but may be present on the sides of the roads themselves. Therefore, driving behavior in these countries tends to be erratic, leading to increased risks that are not fully modeled by existing models. This observation is shared by multiple researchers in the literature. Having described the notions above, our study of interest is divided into several Research Questions (RQs) exploring the main key problems in evaluating various driving behavior models in developing countries. Research questions have been selected to provide directions and suggestions related to modeling driving and mobility behaviors in developing countries. A particular focus is on the microscopic behaviors that can be modeled using the agent-oriented paradigm [21, 22]. The formulation of these questions is based on the experience of the reviewers.

RQ1: *What are the research topics and application domains of the articles related to the topics of this study?* This research question provides an overview of the different research fields considered in the reviewed articles, as well as the associated application domains.

RQ2: *What are the existing driver models that represent the behaviors of the drivers in developing countries?* This research question occupies the priority, as it leads the rest of the categories of questions for the research study. By exploring the kind of driving models popular in developed countries, the literature can be analyzed to understand pre-existing driver behavior models for developing countries. This question can provide ample data that can be analyzed to support an organized pattern in the research study. The preference for the mode of travel of choice among road users in developing countries can also be touched upon if a suitable level of analysis reveals concrete evidence favoring the research question.

RQ3: *What are the suitable models for agent-oriented simulation of driving behavior in developing countries, and how can it be implemented into an agent-oriented simulator?* This research question aims to investigate the suitability of existing models for ABS and identify a suitable model that can follow a streamlined pattern capable of adaptation in any developing country. The question also aims to address the challenges and limitations in implementing the driving behavior model into an agent-oriented simulator, focusing on the requirements and restrictions. The research will explore the nature of road users and traffic conditions to derive a decisive model of driving behavior and suggest techniques to adapt an ABS for advanced research studies.

RQ4: *What kind of driving environment is considered having identified the driver behaviours?* This RQ is related to various environmental means that are crucial in affecting the level of service (LOS) or the operation of road service on an urban roadway or dense highways. Analysis can reveal the reason for the sustainability of homogeneous or heterogeneous traffic conditions in such a place, keeping in mind the preconceived notion that leads to a network smothering the grid when the traffic stream increases its bandwidth. It should help researchers determine and choose the significant properties exhibited in driver behavior.

2.2 Defining review protocol

This section describes the steps of the methodology that are represented in Fig. 1.

2.2.1 Database selection

The databases selected for this study were IEEE Xplore, Academia, and Google Scholar. Although the first two databases were chosen to obtain specific data related to the researcher's topic, Google Scholar was selected for its vast collection of records, including conference articles, Ph.D. and Master's theses, and extensive research articles. Although not peer reviewed, these articles were considered important given the recent increase in interest in the topic. Databases were queried using a set of keywords, including those related to models of driving behavior and recreation strategies in developing countries, as well as broader trends related to transportation in developing countries. According to SLR methodology, a stop criterion is used to limit the total number of articles that are included in the study from the different databases. For this particular study, we have decided to extract papers from the first 25 pages provided by Google Scholar and Academia, and all the pages provided by IEEE database. This stop criterion is designed to limit the investigation time in the scope of two months, which was the time window allowed in the context of the funding projects in this study.

2.2.2 Keyword selection

Since the research area is highly focused on developing countries, the first set of keywords used by the authors of this research study decided to formulate it more refined, which helped in fetching scientific articles involved in driving behavior models for developing countries more directly. This led to the first set of keywords: in Equation (1).

$$\left\{\begin{array}{c}\texttt{driving behavior model,}\\ \texttt{driving models developing countries,}\\ \texttt{car following models India,}\\ \texttt{car following models Africa,}\\ \texttt{existing lane changing models,}\\ \texttt{lane changing models India,}\\ \texttt{lane changes in developing country,}\\ \texttt{lane manoeuvring Africa,}\\ \texttt{gap acceptance models India,}\\ \texttt{single lane road}\end{array}\right\}. \tag{1}$$

After further review and peer discussion, the authors of this study decided to have a more comprehensive keyword set structure that could add more scientific articles. Thus, the second set of keywords was formulated as in Equation

(2).

$$\left\{ \begin{array}{c} \texttt{agent based model,} \\ \texttt{car following model,} \\ \texttt{driving behavior,} \\ \texttt{transport simulation model,} \\ \texttt{gap acceptance model,} \\ \texttt{lane change model,} \\ \texttt{lane model,lane-less,} \\ \texttt{longitudinal behaviors,} \\ \texttt{multi agent model,} \\ \texttt{multi lane model,} \\ \texttt{single lane model,} \\ \texttt{traffic operations,} \\ \texttt{transport models,} \\ \texttt{transport infrastructure,} \\ \texttt{transport lane models,} \\ \texttt{transport microsimulation models} \end{array} \right\}. \tag{2}$$

2.2.3 *Exclusion criteria definition*

The articles that appear in the indexed lists provided by search engines are not all valuable for responding to the RQ. For this reason, almost all literature review methodologies apply a set of exclusion criteria to retain only relevant articles [29, 30]. The authors of this study have defined the following exclusion criteria:

ExC1: *Not a recent research work.* Articles published before 2010, i.e., with a publication year < 2010, are excluded. It is assumed that the nonrecent research is not up-to-date due to the high evolution rate of the driving behavior models and simulation techniques.

ExC2: *Invalid type of articles, the document is a poster or a demo.* It is assumed that a poster or a demo cannot provide enough details of contributions, as there is not enough contributed content for evaluation. Ph.D. theses, Master theses, and technical reports are included.

ExC3: *Invalid type of article, the article is a survey.* It is assumed that the survey articles (i.e., secondary studies) do not provide contributions directly on the driving behavior models and simulation techniques.

ExC4: *Impossible to access the text of the article.* It is impossible to evaluate an article when its text cannot be accessed (PDF download, online text, etc.).

ExC5: *Exclude articles not specific to developing countries.* Ignore topics that are irrelevant or do not contribute to the support of developing countries.

ExC6: *Extended Article.* The article is extended by another article by the same authors. The contributions in the extended article are enclosing those of the original article, so that the latter is excluded.

ExC7: *Exclude articles unrelated to driving behavior.* Literature articles that do not support these topics are ignored.

ExC8: *Exclude articles with macro- or mesoscopic driving behavior.* The proposed models cannot capture the individual properties of the driving behavior.

ExC9: *Cannot be applied in developing countries.* Exclude articles that address a very specific infrastructure model that seems not suitable for transferring the techniques to developing countries or too advanced, i.e., beyond the scope of current trends in these countries. For example, understanding lane change systems for regular vehicles would be useful for analysis rather than analyzing the implications of lane changes that autonomous vehicles face in a prescribed road environment, which would not be appropriate to transfer or suggest a mechanism of such conditions to a developing country. In simple words, analyzing the behavior of autonomous vehicles in the lane and its microsimulations along with the use of mathematical data would not serve the purpose of this research study, as developing countries have not yet reached that phase.

These rules of exclusion criteria are applied to reports in two stages. In the primary coarse-grained step, the articles were possibly disposed of if their titles and abstracts met at any rate one of the avoidance standards. In the subsequent fine-grained step, the excess articles are screened, however, this time perusing the entire body of the article.

2.2.4 *Biases*

To mitigate the subjectivity of the review process, certain measures were taken to overcome biases and resolve conflicts. In particular, each selection step was conducted by a principal reviewer, with an associated reviewer who may complete the analysis of the first reviewer. A third reviewer intervened as a referee to resolve a conflict in the exclusion/inclusion and in the research question answering steps.

2.3 Performing the review

Queries the different search engines with the predefined stop criterion corresponds to 82 articles. Note that since the first selection step screens articles based on their titles and abstracts, some exclusion criteria might be more helpful than others. For this reason, the exclusion criteria ExC1–ExC4 were applied directly during the extraction of scientific articles, leading to the total number of 77 articles. More specifically, the content of the article is screened and the article is excluded if it satisfies at least one of the exclusion criteria. Table 1 shows the results of the selection steps.

Table 1 Number of articles at the different steps of the methodology

Methodology Step	Number of Articles	Percentage
Initial queries in the search engines	82[1]	100%
Excluded articles	52	63%
Included articles	30	36%

[1] 10 with the first keyword set, 72 with the second keyword set.

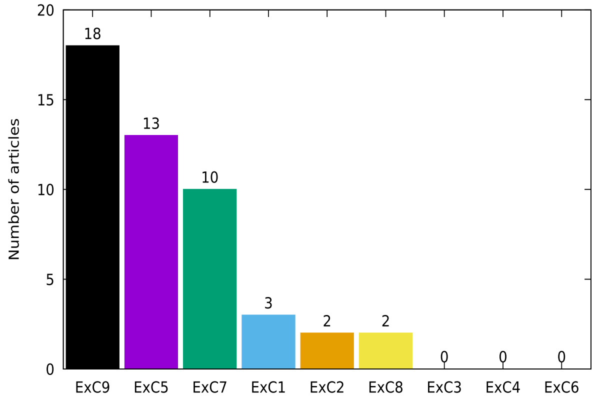

Figure 2 The number of excluded articles per exclusion criterion

As it is illustrated by Fig. 2, the exclusion criteria indicate that the reviewers are focused on recent primary research studies on microlevel driving behavior models that are applicable to developing countries and provide high-quality and informative contributions. ExC5 and ExC9 exclude the highest number of articles (32, 37%), suggesting that the reviewers focus on driving behavior models and, more specifically, on those that are considered feasible for implementation in developing countries. ExC1, ExC7 and ExC8 excluded 15 articles (18%), indicating that the authors focus on recent research related to microlevel driving behavior models. ExC2 excluded 2 articles (2%), indicating that only high-quality and informative publications are being considered. ExC3, ExC4 and ExC6 did not exclude any article, suggesting that all articles found were original accessible primary research studies.

Based on Fig. 3, research on driving behavior models in developing countries seems to have started around 2011 with only one article published that year. The number of publications increased over time, reaching a peak in 2014 with five articles. The trend remained relatively stable until 2019, with a slight increase in the number of publications. However, there was a decrease in the number of publications in 2020. The trend line of annual publications has a slope of 0.376 ± 0.18. This suggests that the topic of driving behavior models in developing countries is gaining more attention and interest from researchers over time.

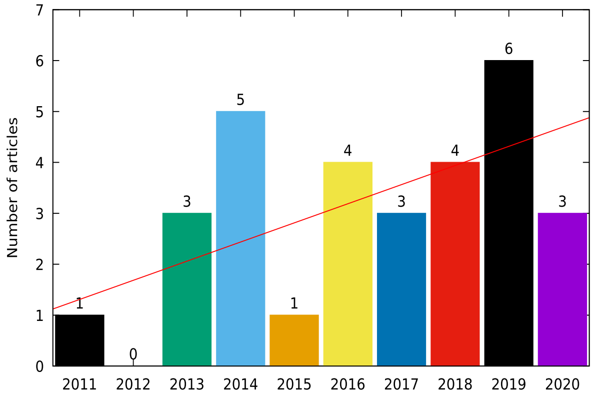

Figure 3 Number of articles per year after the selection steps

According to Fig. 4, it appears that most of the articles (8) were published in India, followed by China (6 articles). The rest of the articles seem to be distributed across several countries with only one article each, suggesting that research on driving behavior models in developing countries is still limited and dispersed across different parts of the world. However, it should be noted that, at this stage of the methodology, there is no information on the quality or impact of the article, so it is difficult to draw any definitive conclusions about the research landscape in this field based only on this information.

Fig. 4 shows that the majority of articles (17) focus on driving behavior models in Asia. This is not surprising as Asia is home to many developing countries and is one of the most populous continents in the world. Africa is also well represented in the table with six articles, which is expected given the large number of developing countries in Africa. Europe has five articles, which could suggest that research on driving behavior models is more focused on developed countries in Europe. South America and Oceania have only one article each, which may indicate that there is less research being conducted in these regions on driving behavior models.

In terms of developing countries specifically, both Asia and Africa have a significant number of articles, with a combined total of 23 articles out of 30. This suggests that there is a focus on developing countries in the research on driving behavior models. However, it is important to note that the table does not provide information on the specific countries that are being studied within each continent, and therefore it is not possible to draw conclusions about the distribution of research across different developing countries.

3 Results of the review and analysis

In this section, we present a comprehensive examination of the results obtained from the SLR. The articles retained

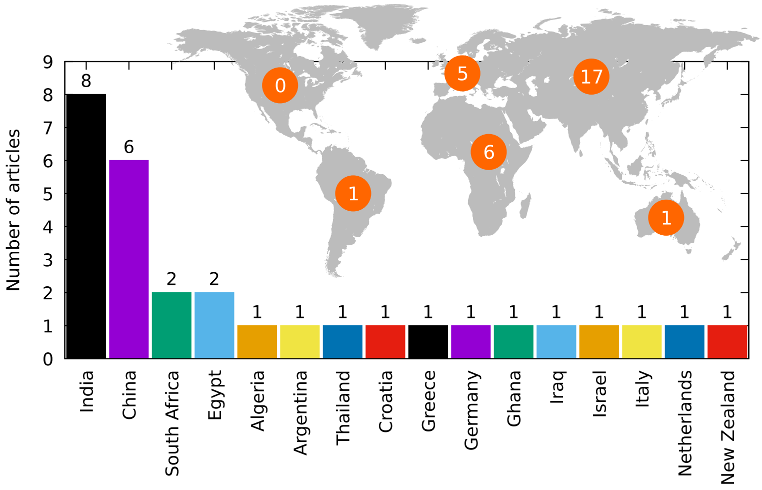

Figure 4 Geographic distribution of articles after the selection steps

Table 2 The reviewed articles per research topic

Research Topic	Articles	Percentage
T1 – Traffic Network Modeling	[31–36]	20%
T2 – Heterogeneous Traffic Flow Modeling	[37–42]	20%
T3 – Road Safety	[43–45]	10%
T4 – Individual Driving Behavior Modeling	[46–57]	40%
T5 – Advanced Driver Assistance Systems (ADAS)	[58–60]	10%

after the selection process are examined, and each RQ defined in Sect. 2.1 is discussed in detail. It is important to note that the results are relevant to the driving behavior models observed in developing countries and their incorporation into an ABS, according to RQ and the exclusion criteria defined in the SLR methodology.

3.1 What are the research topics and application domains of the articles related to the topics of this study? (RQ1)

This section discusses the results and answers RQ1 (cf. Sect. 2.1). It deals with research topics (Sect. 3.1.1) along with application domains (Sect. 3.1.2).

3.1.1 Research topics

Research topics are the subjects or issues that a researcher is interested in when directing the exploration of driving behavior models. They provide general guidance to investigators in characterizing and refining their thoughts. Table 2 and Fig. 5 represent the research topics of the articles reviewed in the study. These topics cover different aspects related to driving behavior models and simulation techniques, such as traffic flow and network analysis, driver behavior and psychosocial aspects, vehicle speed, and advanced driver assistance systems. Details on each topic are provided below.

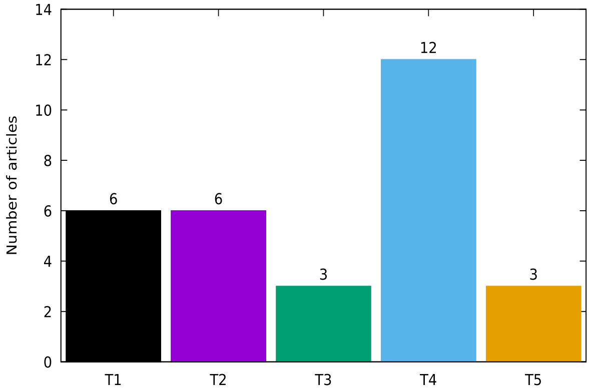

Figure 5 Number of articles per research topics

T1: *Traffic Network Modeling.* Travel choice comes into play when defining a traffic network [34–36] that forecast the behavior of the system using timestep approach and ABS. Among the articles that are found in this research topic, several focus on the Highway Capacity Manual (HCM) [31–33], which is a conflicting technique that uses the Tanner formula to determine the capacities of the roads.

T2: *Heterogeneous Traffic Flow.* Mixed traffic flow is always prevalent with sensitized urban road flow, which is primarily prone to congestion [37–42]. Usually, the capacity for traffic and the level of service in traffic operations all hinder the free flow condition, which alters the speed difference and the critical gap threshold. This traffic condition is very prevalent in almost all developed countries and leads to no lane.

T3: *Road Safety.* The vehicle-pedestrian interaction influences driving behavior with the safety of the primary concern [43–45]. This fact is also related to operational traffic safety and accidents in geometric elements of urban roundabouts.

T4: *Individual Driving Behavior Modeling.* Lane change, vehicle interaction, road vehicle trajectory are all common insights for a driving behavior out of which the frequency of lane change and volume are crucial to study [47–50].

Driving is subjected to various alteration dynamics that deals with the principles of longitudinal and lateral motions [55, 56]. A theory of consensus in ABS studies the analysis of longitudinal control and reward function.

Acceleration and deceleration patterns and determining speed characteristics help to make decisions about driver behavior and speed of vehicles [51, 52, 57].

Most of the practicality of driving behavior patterns comes into play during uncontrolled intersections, roundabouts, and signalizations. The scientific literature suggests binary Logit left turn gap acceptance, clearing behavior approach, and gap acceptance decision as some of the recommendations [46, 53, 54].

T5: *Advanced Driver Assistance Systems (ADAS).* This concept along with the following behavior of the vehicle using automated driving systems with the acceptance theory of gaps with the concept of gray system theory, explains the role of the vehicle preceding the first path of the host vehicle by remarking on the car following correlative degree [58–60].

It is important to note that some of these topics, such as road safety, traffic flow, and driver behavior, are crucial for developing countries, where road safety is a major concern and traffic flow is often not optimized due to inadequate infrastructure. Therefore, research in these areas can help improve transportation systems in developing countries and reduce the number of accidents on the roads. Some articles cover more than one topic and were marked as exceptional cases. To normalize the weights given by each article to the research topics distribution, the most predominant topic has been labeled the head topic for which the other aspects and concepts are covered under them.

3.1.2 Application domains

RQ3 covers not only research topics, but also the use of behavior models and simulation techniques in transportation applications. This refers to applied research, where scientific studies aim to solve practical problems in specific areas. Table 3 displays the number of articles per application domain. It should be noted that several articles address multiple domains, so the most prevalent domain per article was selected to standardize the loads assigned to each domain. The resulting application domains are urban and rural roads, metropolitan regions, roads, behavioral interventions, intelligent transport systems, and road network planning.

Table 3 The reviewed articles per application domain

Application Domains	Articles	Percentage
D1 – Urban and Rural Roads	[31, 37, 40, 46, 49, 57]	20%
D2 – Metropolitan Region	[34, 39, 42, 51, 53–55]	23.4%
D3 – Highways	[32, 38, 50, 56]	13.3%
D4 – Behavioral Interventions	[35, 44, 47, 52, 59]	16.7%
D5 – Intelligent Transport Systems	[41, 48, 58, 60]	13.3%
D6 – Road Network Planning	[33, 36, 43, 45]	13.3%

D1: *Urban and Rural Roads.* The study author discovered that many authors provided a strong reason to investigate concepts that support the function of the urban and rural roads. Interesting highlights include handling unsignalized convergences, adjusting acceleration/deceleration models for more accurate speed profiles, using microsimulation and mathematical modeling to improve intersection capacity, left-turn gap recognition in uncontrolled intersections, maintaining gap values between vehicles on single-lane country roads, and collecting vehicle data during on-road driving to study real-world traffic interactions. This domain includes six articles and constitutes 20% of the total articles reviewed. Articles in this domain focus on modeling traffic networks and heterogeneous traffic flow on urban and rural roads, as well as road safety.

D2: *Metropolitan Region.* The articles that discussed threats to urban and arterial roads covered relevant ideologies. Interesting highlights include: addressing Braess paradox in traffic networks, modeling mixed traffic conditions for developing countries, addressing aggressive drivers at T intersections, developing microsimulation models for Bangkok intersections, using signalization options to improve traffic flow in Ghana, recommending VISSIM for analyzing heterogeneous traffic in India with some adjustments, and using the proposed model to build simulators like SUMO, SiMTraM, and HETEROSIM. This domain has five articles, representing 23% of the total articles reviewed. Articles in this domain focus on traffic flow, individual driving behavior, and road safety in metropolitan regions.

D3: *Highways.* Many articles describe roads as a chaotic environment in which each driver tries to maintain his own comfort. To address this problem and find efficient strategies, concepts such as recognizing speed-density relationships, distinguishing systems to accurately assess capacity for Indian highways, applying stochastic models for impact-free speed control, and maintaining distance between vehicles to prevent crashes have been proposed. This domain includes four articles, representing 13% of the total articles reviewed. Articles in this domain focus on modeling the traffic network, traffic flow, and vehicle speed on highways.

D4: *Behavioral Interventions.* The researcher has identified potential areas for future studies to improve road transportation through behavioral interventions, including the capture of car follower behavior for the prediction of accidents, the treatment of road safety and habitual driver behavior in African countries and their sociopsychological effects, tailoring interventions for young drivers in Egypt, teaching road users to focus on speed and distance through pedestrian behavior studies, and investigating human factors that influence merging behaviors through focus group studies. This domain has five articles and represents 17% of the total articles reviewed. Articles in this domain focus on individual driving behavior and the effects of various interventions, such as advanced driver assistance systems (ADAS), on driving behavior.

D5: *Intelligent Transport Systems.* Research articles focused on promoting the principles of Intelligent Transport Systems, with highlights including: (a) Using ITS to address social problems such as congestion, traffic safety, and air pollution through Advanced Driver Assistance Systems (ADAS); (b) Considering the particle filter approach as a promising tool for developing ATIS applications; (c) Extracting lane change segments from driving sequences by modeling and recognizing patterns in steering angle through large-scale on-road data collection and processing; (d) Conducting multilane behavior analysis to benefit ADAS adaptability and acceptance by drivers. This domain includes four articles, which constitute 13 of the total articles reviewed. Articles in this domain focus on the use of intelligent transport systems (ITS) to improve traffic flow, safety, and efficiency.

D6: *Road Network Planning.* To assess the maturity of the road environment, planning and transport networks are discussed to adapt to the future settings. The researcher observes the following highlights: (a) Dynamic traffic assignment to calculate travel time. (b) Optimizing geometry, TE, and TS for unsignalized single-lane urban roundabouts to help policy makers, civil and traffic engineers. (c) Designing multilane roundabouts to address transportation problems using microsimulation for real-world case studies. (d) Extracting risk indicators to predict the likelihood of an accident using a high-resolution, spatially explicit, dynamic agent-based simulation model. This methodology can assist transportation designers in understanding how road facilities or installation features can affect road user safety. This domain has four articles and represents 13% of the total articles reviewed. The articles in this domain are focused on road network planning and design, as well as traffic network modeling.

Most of the articles (23.3%) focus on the application domain of metropolitan regions. This is not surprising, as urban areas are more likely to face traffic congestion and related problems, which require effective management and planning. Urban and rural roads are the second most common application domain, accounting for 20% of the articles. This highlights the importance of addressing traffic-related challenges in both urban and rural areas. Highways and road network planning are also significant application domains, accounting for 13.3% each. These domains are important because highways are major corridors for transportation and road network planning is crucial for designing efficient transportation networks. Behavioral interventions and intelligent transport systems are also important application domains, accounting for 16.7% and 13.3% of the articles, respectively. These domains address the human element of traffic management and the use of technology to improve traffic flow. The distribution of articles in the different application domains suggests a well-rounded approach to traffic management, paying attention to urban and rural areas, highways, road network planning, behavior interventions, and intelligent transport systems.

3.2 What are the existing driver models that represent the behaviors of the drivers in developing countries? (RQ2)

Driving behavior models are based on road traffic conditions which vary depending on the country. Several models were proposed in the literature to reproduce driving behaviors. Models may consider homogeneous or heterogeneous entities in the model, such as light vehicles, heavy vehicles, bikes, etc. Models also focus on the two major motions for driving: the longitudinal behavior, which consists of deciding the acceleration or speed to be applied according to external conditions, and the lateral behavior, which is used for controlling the position of the vehicle on the road width or when changing lane. Table 4 provides a summary of the articles reviewed on the models used and their categories. The different types of models have been classified by Arkatkar [41] and shown in Fig. 6. Basically, driving behavior is divided into two families: (i) longitudinal models (or car-following models) that enables to compute the acceleration to apply to a vehicle according to a

Table 4 The reviewed articles per type of driver behavior model. "Ho" and "He" columns indicate if the articles focus on homogeneous or heterogeneous behaviors, respectively. "Lo" and "La" indicate if the articles propose a longitudinal or lateral driving behavior, respectively

Driver Model	Ho	He	Lo	La	Articles	Percentage
HCM analysis and equation-based model	✓		✓	✓	[31–33, 40, 41, 44, 47]	23.5%
Equation-based model & Signal processing	✓		✓	✓	[48, 49, 55]	10%
Wiedemann car-following model	✓		✓		[51, 52, 54]	10%
Logit mathematical model	✓		✓		[46, 53]	6.7%
Multi-criteria and simultaneous multi-objective optimization		✓	✓	✓	[43, 45]	6.7%
Agent-based model and dedicated car following	✓		✓		[34, 36]	6.7%
PARAMICS model		✓	✓		[37, 50]	6.7%
Ad hoc equation-based model		✓	✓	✓	[42]	3.3%
Ad hoc equation-based model		✓	✓		[57]	3.3%
Ad hoc equation-based model		✓		✓	[59]	3.3%
Markov model for car following	✓		✓		[35]	3.3%
GIPPS car following model	✓		✓		[38]	3.3%
Optimal velocity robust car-following model	✓		✓		[56]	3.3%
Task-Capability-Interface model	✓		✓		[58]	3.3%
Grey System Theory	✓		✓		[60]	3.3%
Signal processing from LIDAR dataset	✓			✓	[48]	3.3%

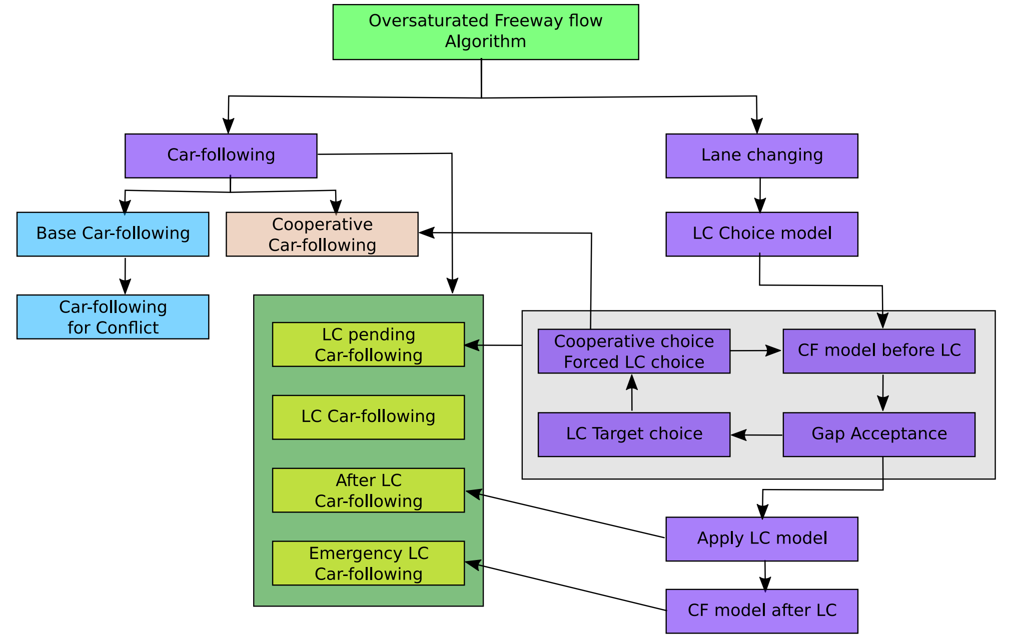

Figure 6 Types of simulation models of the individual driving behavior that are used in developping country applications [41]

specific driving behavior. (ii) Lateral control or lane changing models that enables one to simulate or control the left-right motion of the vehicle on the roads.

The articles in Table 4 cover various aspects of traffic analysis and simulation. Among them, the Highway Capacity Manual (HCM) method is applied in seven articles. Siva et al. [31] highlighted the importance of unsigned intersections in urban and rural settings. The article introduces the conflict technique, a pragmatic approach to analyzing unsigned intersections under mixed traffic conditions, providing a methodology to calculate the capacity of intersections. The proposed approach is applied in the Visakhapatnam region, India, comparing the results obtained from the proposed technique with the 2000 HCM [31]. Recognizing global heterogeneities in traffic conditions, [32] emphasized the need for region-specific methodologies, leading to the development of the Indian Highway Capacity Manual (Indo-HCM). Furthermore, Giuffrè et al. [33] and Jima [44] explored the estimation of the equivalents of passenger cars for heavy vehicles at single-lane roundabouts, highlighting the importance of an accurate estimate of capacity and level of service. The role of free-flow speed in assessing the Level of Service (LOS) for two-lane highways is explored, with a focus on examining methodologies under heterogeneous traffic conditions in India [40]. The study introduces a novel measure, the speed difference, and identifies the critical gap threshold value of 10 seconds as suitable for calculating the free flow speed under such conditions [40, 41]. Furthermore, the article discusses a comprehensive cross-sectional study involving nonprofessional drivers in South Egypt, with the objective of evaluating driver behavior using the Arabic version of the Driver Behavior Questionnaire [47]. [47] underscored the importance of region-specific methodologies, the development of tools such as Indo-HCM, and the consideration of heterogeneous traffic conditions in improving the precision of traffic analysis and simulation studies.

The two-part article [48, 49] focused on studying lane change behaviors at the tactical level from an on-road perspective, with a particular emphasis on analyzing interactions between an ego vehicle and surrounding vehicles during the lane change procedure. Part I focuses primarily on vehicle trajectory collection, while Part II delves into lane change extraction and scene-based behavioral analysis. The paper introduces a novel system to collect vehicle trajectory on the road, using an instrumented vehicle equipped with multiple horizontal 2-D lidars that provide 360-degree coverage. The software is developed to fit laser points from all lidars onto a vehicle model, ensuring accurate state estimations of occluded data and robust data association in multiviewpoint sensing. Extensive investigations validate the performance of the system, resulting in a large set of trajectory developed during road driving in Beijing, covering a total distance of 64 km with more than 5700 environmental trajectories. The system is the first of its kind to automatically collect all-around vehicle trajectories during road driving, demonstrating high-quality performance for studies of driving behavior from an on-road perspective, addressing vehicle interactions in real-world traffic at the trajectory level [48, 49]. In a related context, another paper [55] introduced a new model for traffic on broad roads where drivers do not strictly adhere to the lane discipline. The model considers both longitudinal and lateral motions, assuming that driver reactions are influenced by surrounding vehicles, obstacles, and unmodeled entities in visibility cones. The network of influences is represented by "influence graphs", and in congested traffic, a time-invariant influence structure leads to homogeneous driver behavior, resulting in a layered formation with fixed distances between vehicles. In sparse and heterogeneous traffic, the velocity and inter-vehicle separations in the modeled vehicles are uniformly bounded. Experimental verification of the model is conducted using videos of typical traffic in Mumbai city, India, recorded and processed using image processing techniques. The proposed model accurately predicts complex maneuvers, such as overtaking, sideways movements, and collision avoidance, demonstrating its applicability to real-world traffic scenarios.

Three articles use the Wiedemann car following model [51, 52, 54]. They highlight the growing motorization on highways in India, mainly with 2-wheeler and 3-wheeler vehicles, which has negatively impacted both bus and car transport [51, 52, 54]. This surge in motorization has led to highly heterogeneous traffic conditions, characterized by diverse static and dynamic features of different vehicle types. Given the complexity of the system, the text emphasizes the necessity for a microscopic simulation model to analyze these conditions effectively. It notes that stochastic models, with their inherent randomness, offer superior quality compared to deterministic models. The microscopic nature of traffic simulation is particularly advantageous as it captures the psychophysical behavior of vehicular interaction. VANET model is introduced in the VISSM traffic simulator as a tool to understand the nature of mixed traffic through discrete, stochastic, and time-step-based analysis. In summary, the work underscores the importance of using traffic simulation, particularly VISSM, to gain insight into the dynamics of mixed traffic in India, using a discrete and stochastic approach for time-step-based analysis [51, 52, 54].

Serag [46] focused on accepting left-turn gap in developing countries in the form of a binary logit left-turn gap acceptance model based on field observations 1496 in Egypt. The study distinguishes between gap and lag, identifying influencing factors such as gap type, time interval, driver time to turn, and oncoming driver yielding behavior. Equations are developed and applied to estimate critical gaps and lags for different scenarios, revealing values lower than those of developed countries, indicating riskier driver behavior in developing countries. Gap acceptance at T-Intersections in India is studied by Dutta and Ahmed [53]. They focus on uncontrolled T intersections in the North-East region of India, analyzing and modeling the acceptance behavior of gaps of minor street drivers. The results indicate aggressive behavior, not only due to waiting times, but also to a lack of respect for traffic rules. Binary logit models are developed considering factors such as the duration of the gap, the clearing time, and the aggressivity of the driver. Critical gaps are estimated for aggressive and non-aggressive drivers, emphasizing the importance of considering clearing time and driver behavior in critical gap calculations. Thunig and Nagel [34] addressed Braess's paradox in the agent-based transport simulation MATSim, distinguishing between scenarios with and without spill back effects. The study observes two types of paradox and emphasizes the importance of capturing spill-back effects for realistic modeling. Furthermore, the integration of activity-based models with dynamic traffic assignment is explored, with adjustments made to enhance the performance of MATSim, exemplified using the city of Baoding, China [34, 36]. Ochungo [37] explained the steps in the design process of the decongestion of the interchange “GSU” in Nairobi, Kenya. The design process involves microsimulation modeling using PARAMICS and AutoCAD Civil 3D geometric modeling techniques. The paper outlines the workflow steps that led to the final choice of the interchange configuration’s shape and form, emphasizing the efficacy of microsimulation models in supporting geometric remodeling for enhanced capacity and flow. Al-Jameel and Kadhim [50] focused on rural roads in Iraq, with the aim of enriching the area of developing road simulation models calibrated with field data. The objectives include investigating driver behavior, developing a simulation model and calibrating it graphically and statistically with field data. The developed model is compared with the well-known S-Paramics model, demonstrating greater precision in representing driver behavior on Iraqi rural roads.

The rest of the studies improve our understanding of traffic behavior, developing models for simulation and optimization, and addressing specific challenges in various traffic scenarios. Bayomy and Gomaa [35] introduced a model that incorporates a stochastic Markov regime switching model to estimate individual driver characteristics and extract different characteristics of the driving regime. The proposed model considers trajectory data such as velocity, acceleration, space gap, and switching features, allowing classification of normal and rare car following events. It has applications in crash prediction and driver assistance systems. Maurya and Budhkar [38] addressed the chaotic nature of Indian traffic, characterized by various types of vehicles and lack of discipline in the lane. An attempt is made to quantify the heterogeneity parameters for Indian traffic in existing car-following models, creating a modified model. The developed simulation model is used to replicate Indian traffic conditions, demonstrating a satisfactory real-time simulation of traffic characteristics in Delhi. Morita et al. [42] presented a microsimulation model for mixed traffic conditions in Bangkok, Thailand. The model considers the traffic volume, geometric structure, signal control, and driving behavior parameters obtained by video observation. Sensitivity analysis explores various measures of traffic jams, highlighting the importance of combining measures to effectively reduce congestion. Papathanasopoulou and Antoniou [39] focused on modeling driving maneuvers in a mixed traffic scenario in developing countries. The methodology, based on data-driven models, simplifies the modeling of longitudinal and lateral movements. The study explores the identification of significant lateral changes, particularly in situations of lane change. Waizman et al. [43] and Pilko et al. [45] proposed a multiobjective optimization model for single-lane urban roundabouts, with the aim of simultaneously optimizing geometry, traffic efficiency, and safety. The model uses an analytic hierarchy process for evaluation and classification. Preliminary validation identifies an optimal geometric alternative that improves traffic efficiency and safety. Messaoudi [56] proposed an optimal velocity robust car-following model (OV-RCFM) considering control uncertainty. The objective of the model is to produce reliable and collision-free velocity control in uncertain simulation environments, contributing to the development of intelligent transportation systems. Altamira et al. [57] investigated the acceleration/deceleration patterns of light vehicles on rural roads in Argentina. Using GPS logger and camera data, the study explores patterns on approach tangents, along horizontal curves, and on exit tangents. The results show variability in the rates depending on factors such as tangent length, curve radius, and longitudinal slope. Hoogendoorn et al. [58] introduced a theoretical framework that integrates the Task-Capability-Interface model into the Intelligent Driver Model to model adaptation effects in longitudinal driving behavior after driver distraction. Simulations demonstrate the suitability of the framework in describing the effects of distraction. Li et al. [59] addressed the complexity of vehicle merging, focusing on merging position selection behavior and heterogeneity among merging drivers. A finite mixture of linear regression models is developed to describe the selection of merged positions, taking into account both lateral and longitudinal factors. The model identifies driver heterogeneity and improves accuracy in microscopic traffic simulation. Yu and Wang [60] introduced Grey System Theory to analyze car-following behavior in multilane driving. The method establishes differences between following a host-lane vehicle and an adjacent-lane vehicle, emphasizing the need to explore drivers’ behavior rules in multilane driving for advanced driver assistance systems.

The answer to RQ2 describes various models used for traffic management and decongestion processes in different countries. The models vary in their level of sophistication, incorporating factors such as vehicle heterogeneity, lateral interaction, and road geometry. The use of microsimulation models is highlighted for decongestion design processes in African countries, where road conditions are heterogeneous. Discrete choice models are used for pedestrian interaction with vehicles, but do not represent events that occur after pedestrians or drivers make a decision. Finally, the passage concludes that car follow-up models that support gap acceptance behavior should be given high priority for consideration when using a suitable ANS approach, but the model is limited to countries driving on the left-hand side.

Table 5 The reviewed articles per type of agent-based model for reproducing driving behaviors

ABM Driving Model	Articles	Percentage	Related Articles
Wiedermann/VISSIM	[51, 52, 54]	10%	[68, 74]
Gipps/MATSIM	[34, 36, 38]	10%	[39, 68–73, 75]
PARAMICS	[37, 50]	6.7%	[68, 75]
Data-driven or activity-based model	[39]	3.3%	[71–73]
Optimal velocity robust car-following model	[56]	3.3%	
No specific ABM	[31–33, 35, 40–49, 53, 55, 57–60]	66.7%	

3.3 What are the suitable models for agent-oriented simulation of driving behavior in developing countries, and how can it be implemented into an agent-oriented simulator? (RQ3)

The answer to this RQ is structured in two subsections dedicated to the two parts of the questions.

3.3.1 ABS models for driver behavior in developing countries

The rapid increase in heterogeneous traffic conditions poses challenges to lane analysis and car follow models, especially in locations with poor lane management or deteriorating flow patterns. Researchers have used traffic simulation frameworks to develop better driver behavior models [61] and gain insight into driver behavior [62, 63].

Table 5 synthetizes the articles that contribute in the field of agent-based modeling (ABM). However, a large part of the selected articles (66.7%) do not contribute explicitly in ABM, depicting the fact that agent-based microsimulation is one of the major approaches in the field of traffic simulation since a decade, as illustrated by the number of related articles in the last column of Table 5.

(i) *ABM for longitudinal and lateral driving behavior:* The majority of the proposed models focus on the longitudinal behavior of the drivers. They are deterministic models that ensure collision-free speed control [64]. Among the most commonly used ABM models, the Wiedemann [65] model (on the VISSIM platform), the Gipps [66] model (on the MATSIM platform), and PARAMICS could be observed in the reviewed articles. They are used to model the behavior of individual vehicles using a car follow model and a lane change model [67].

According to Mehar et al. [68], Wiedemann [65] model cannot reproduce mixed traffic conditions that affect Indian roads. On the contrary, the Gipps [66] model has shown potential for better field condition replication than other models in unstable states. However, lane-based models are not always applicable in heterogeneous traffic conditions prevalent in developing countries [68].

Many examples of the use of ABM with MATSim or VISSIM for the modeling and the simulation of driving behavior in developping countries could be found in articles that are outside the selection criteria of this study [36, 39, 68–73].

(ii) *Activity-based models in conjunction with ABM:* Data-driven approaches, such as activity-based models, have shown promise in providing flexible car follower models and a more reliable representation of driving behavior [39].

(iii) *Dynamic Traffic Assignment in conjunction with ABM:* When coupled with dynamic traffic assignment, ABM can help account for the impact of traffic conditions on individual travel behavior, such as location of activity and route choice. Although the simplified Gipps [66] model generally has weak parts related to ABM, it can potentially become a fully integrated ABM and DTA structure capable of modeling traffic-based travel demand and simultaneously adjusting activity types, locations, and sequence.

For answering RQ3, the existing models of individual driving behaviors discussed previously are suitable for ABS. ABS involves modeling the behavior of individual agents, such as drivers, and their interactions within a larger system. The driving behavior models, such as the Wiedemann [65] or Gipps [66] models, are designed to capture the behavior of individual drivers in different situations and can be used to simulate their actions and interactions within a larger traffic system.

In fact, many ABS frameworks, such as MATSIM or VISSIM (as well as two other major traffic simulation frameworks: SUMO and GAMA) already incorporate these driving behavior models to simulate individual driver behavior and interactions. Various applications have been developed, such as Treiterer [76] and Wu et al. [77]. However, several works such as [78, 79] have relied on ad hoc rules to model the traffic of developing countries without sustainable numerical properties, leading to limitations in the reliability of the simulated directions. To address this problem, a more comprehensive and numerically rigorous model is necessary and was studied in different research works [23, 76–84].

Furthermore, the problem of pedestrian-vehicle interaction in developing countries is a concern [43]. Waizman et al. [85] proposed a dynamic agent-based simulation model (named SAFEPED) to model and simulate the discrete choice of drivers and pedestrians and assess accident risks [43]. Solving the conflicts among drivers and pedestrians is based on the Gibson hypothesis of affordance [86]. Moreover, Braess's paradox is a phenomenon that states that, by adding a link to the network, there can be an increase in the total travel time of a user equilibrium [87, 88]. It can be simulated using MATSIM with time-dependent travel times. The inquiry whether a situation contains Braess's paradox is complex, and finding a mechanism to identify Braess links, such as links that should be removed, is much harder [75].

3.3.2 *Key properties of the individual behavior models*

According to Rossi et al. [89], Kim et al. [90], computer simulations have the potential to overcome some of the limitations of transport field studies. However, the precision of the simulations depends on the precise modeling of vehicle components and driver behavior, especially during critical maneuvers [91]. An accurate and reliable reproduction of driving behavior is essential to create a realistic microscopic simulation of urban traffic [92]. The following properties are critical for this purpose:

- Traveled distance for every movement in each approach;
- Times of arrival and departure on reference lines for every vehicle from each stream;
- Approach speed of the vehicles;
- Volume at unsignalized intersection development insightful.

The study found that traffic flow in western countries is characteristically variable with marginal variation, contrary to the large variation found on the roads of developing countries [31].

Another important factor to consider is the driver's speed profile, which can aid in critical analysis. Speed profiles describe the operating speed of vehicles on highways and are used to estimate fuel consumption, exhaust emissions, operating costs, and travel time, and to perform a consistency evaluation of the mathematical design of the road. Speed profiles are generated using mathematical models for speed calculation and acceleration. Speed calculation is widely studied in the literature, and it is a historical fact that on level curves, the radius of the curve and the speed at the approaching tangent are the main factors that explain the operating velocities [93–96]. Additionally, acceleration models are necessary to describe the speed profiles when passing through curves to/from straight-tangent changes. A power analysis through linear regression or algorithm models such as ANOVA would usually help to achieve this purpose.

The behavior of car following varies according to the driving situation and can be divided into five regimes: (i) acceleration, (ii) approaching, (iii) braking, (iv) stable following, and (v) free flow. The driver's behavior in each regime changes depending on the driving situation. The approaching situation starts when the following vehicle becomes close to the lead vehicle and ends when the following vehicle reaches the desired safe distance of stable follow. In the case of a slowing situation, the following vehicle becomes too close and is faster than the lead vehicle, so the follower decelerates slightly [35].

The acceptance behavior of the gap is influenced not only by intersection characteristics, vehicular characteristics, opposing flow and type of control, but also by subjective elements such as the mental and *socioeconomic status of the drivers*, *weather conditions*, *asphalt and light conditions*, and *vehicle occupancy* [53, 97–102].

Drivers were found to *behave aggressively* due to their disregard of traffic rules rather than being upset by the inaccessibility of a suitable gap. *Age* also plays an important role in the decision-making process for gap acceptance, with adults making better decisions than older children, who make better decisions than younger children. Gap assessment involves making judgments about whether it is possible to complete a maneuver before an oncoming vehicle arrives and requires considering both the distance and speed of the approaching vehicle.

3.4 What kind of driving environment is considered having identified the driver behaviours? (RQ4)

Agent-based simulations, when implemented with driving models, can adapt to these environmental attributes [103]. The heterogeneity of entities and infrastructures is an essential aspect of traffic modeling and simulation, and it is important to develop models that can accurately capture these characteristics to improve traffic flow and safety in developing countries.

3.4.1 *Heterogeneity of entities*

Heterogeneous traffic in India comprises buses, trucks, light commercial vehicles, cars, three-wheelers, two-wheelers, bicycles and tricycles [104]. Dynamic traffic models have been developed for Indian conditions, where lane discipline is rarely observed, and the distances between vehicles can vary significantly [55]. These models take into account differences in vehicle characteristics, road user behavior patterns, and traffic flow patterns, and can provide a more realistic representation of traffic dynamics on Indian roads.

3.4.2 *Heterogeneity of infrastructures*

Each developing country has a unique driving environment characterized by factors such as unsignalized intersections, increased roundabouts, heterogeneous traffic conditions, traffic demand, geometric restrictions of the road, road elements, and behavior patterns of road users. Researchers initially focused on traffic control and limits in the road network, but efforts have been made to improve flow efficiency [105, 106]. The development of traffic light planning is a commonly used method, but microsimulation models do not explicitly yield a limit as a performance measure [107]. Delays at intersections are classified into several types and roundabouts are common bottlenecks on metro routes [108]. Computational configurations for traffic analysis generally cannot model irregular configurations [109, 110].

Various models to determine roundabout capacity under mixed traffic conditions suggest that it is strongly influenced by mathematical factors [111]. Research on roundabouts in different countries, especially single-lane roundabouts (signalized and unsigned) in urban areas, has shown that proper design and modeling can significantly improve traffic efficiency (TE) [112–116] and traffic safety (TS) [117–119]. However, these and other studies [120–122] have shown that current design and modeling guidelines are not always suitable for situations that require simultaneous optimization of calculations, TE, and TS. Interestingly, many countries in Africa and Asia still construct numerous roundabouts for their highway sectors, but often overlook the beneficial characteristics of roundabouts, as these structures have a unique set of design requirements that must be adapted to each road environment [123].

Geometrical factors such as the circle radii, the entry/exit radii, the entry/exit approach width and the direction of the vehicle path have been improved [124], while the link between the speed of the vehicle path configuration through the roundabout and the observed vehicle speeds has been studied.

4 Challenges and research directions

In this section, the main challenges and research directions related to the driving model in developing countries are listed. These research directions are mentioned in articles in the reviewed literature or identified based on the own experiences of the authors of this article. All the research directions and work perspectives found have been synthesized in three major research directions that are related to the initial RQ, as illustrated by Table 6.

4.1 RD1: heterogeneity of traffic entities

Modeling heterogeneous traffic, which includes vehicles such as 2- or 3-wheelers, trucks, and pedestrians, is not completely accurate at the macroscopic and microscopic levels. Empirical evidence indicates that drivers exhibit varied responses when encountering different types of vehicle, particularly in scenarios such as narrow roads or roundabouts, where the geometry of the road affects vehicles differently depending on their maneuverability.

Due to the significant heterogeneity and unique driver behavior on Indian roads, which differs from other developing countries such as China and Indonesia, the principles developed for other countries cannot be easily applied to Indian traffic conditions without establishing suitable adjustment factors. Recognizing this information gap, the CSIR Central Road Research Institute has undertaken the Indonesian HCM project to develop a road capacity manual specifically for Indian conditions, covering the full range of road facilities available in the country [32]. Indonesian HCM considers the heterogeneous traffic conditions commonly found on Indonesian roads. It defines the base conditions for its multipath highways differently, including 3.5 m traffic path or lane widths, shoulders of an effective width of 1.0 m for each road, a divided road, flat terrain, no roadside improvements, very low side grinding, functional class of the road as arterial street and more than 70% of the segment with a view distance greater than 300 meters. However, the Indonesian HCM takes into account certain roadside events in the section, such as the presence of pedestrians, stops made by public transport and other vehicles, vehicles entering and leaving roadside premises, and slow moving vehicles, while limiting the weighted frequency of such events to less than 50. Furthermore, the Indonesian HCM specifies the sight distance requirements, which are not included in the US-HCM, considering local conditions [32].

In the real world, the stochastic environment of vehicle control actions can result in control uncertainty, mainly due to tire slip and brake lock-up. Applying the same acceleration at the same speed could lead to different and often unpredictable outcomes. Consequently, drivers can

Table 6 Relationship between the initial research questions (RQ) and the synthetized major research directions (RD)

Research Questions	Research Directions
RQ1 – What are the research topics and application domains of the articles related to the topics of this study?	This RQ does not lead to a specific RD. Answering this question increases the general knowledge of the reader.
RQ2 – What are the existing driver models that represent the behaviors of the drivers in developing countries?	*RD1* – Heterogeneity of traffic entities; *RD2* – Dynamic and Virtualized Structure of Roads
RQ3 – What are the suitable models for agent-oriented simulation of driving behavior in developing countries, and how can it be implemented into an agent-oriented simulator?	*RD1* – Heterogeneity of traffic entities; *RD2* – Dynamic and Virtualized Structure of Roads
RQ4 – What kind of driving environment is considered having identified the driver behaviours?	*RD2* – Dynamic and Virtualized Structure of Roads; *RD3* – Optimal Infrastructure Design

become uncertain about the specific result of their actions, leading to control uncertainty [64].

Among the types of entity that could be found in a traffic system, the autonomous vehicle (AV) has a particular position. In fact, the arrival of AV may constitute another significant turning point in the development of our daily lives, the urban environment, and human civilization as a whole. An extremely disruptive technology, whose use will affect parking problems, air pollution, travel habits, road safety, and other elements of daily life. In developed countries, autonomous vehicles are expected to be widely used for daily transportation in the next ten years. Developing countries would not be able to implement it for at least another fifty years [125]. However, it might soon be used in specific applications [125].

The recent study undertaken by Kumar et al. [125] cites the main research directions that researchers could consider. One of them is related to cybersecurity risks. It constitutes one of the main barriers to the adoption of self-driving vehicles, including in developing countries. This study may help explain the interdependence of obstacles for organizations and countries that try to promote the use of autonomous vehicles in developing countries. A policy for autonomous vehicle research must be developed in conjunction with standard testing and homologation procedures. Adopting a legislative framework and uniform safety standards is also necessary for organizations and nations. Developing countries must embrace a methodical approach to planning, implementing, and maintaining autonomous vehicles to win consumers' trust and alleviate concerns about their safety. In a similar approach to the one in this article, Kumar et al. [125] highlighted the main obstacles to the general public's acceptance of autonomous vehicles, but it does not provide a numerical estimate of how these obstacles will affect the stated goal. Furthermore, the approach has not been statistically tested and is dependent on professional judgment.

4.2 RD2: dynamic and virtualized structure of roads

In certain developing countries, such as India, a common feature is the lack of strong lane discipline, resulting in vehicles often straddling between lanes. Empirical evidence has shown that this results in an increase in road capacity but a decrease in speed profile. Although this phenomenon can be incorporated into macroscopic simulation models through certain adjustments, ongoing research is attempting to model its implications at the microscopic level, such as in trajectory planning and car-following speed adaptation. To advance these studies, an integrated model is necessary, together with further comparisons with field data from different countries.

Advanced Driver Assistance Systems (ADAS) offer considerable potential to change driving behaviors. Their effectiveness is compromised when drivers prone to risky behavior persist in engaging in distracting activities. Although real-time warnings have been shown to improve driving behavior, the sustained impact of warning-based ADAS on curbing driving distractions among light commercial vehicle (LCV) drivers remains uncertain [126]. The findings indicate that warning-based ADAS, which provides real-time alerts, effectively reduces distraction events that lead to driver inattention, forward collisions, and lane departures. The research reveals that passive and active monitoring systems, when combined with coaching and rewards, significantly reduce aggressive driving behaviors related to harsh acceleration (by 76%) and harsh braking (by 65%) [126]. These research results offer valuable support to road safety stakeholders in developing countries, helping them develop risk assessments based on warning-based ADAS, launch targeted campaigns to reduce driving distractions, and implement effective driving coaching programs.

In countries such as India, numerous road projects have been implemented to facilitate travel and connectivity throughout the country. However, HCM expectations for commercial roads, where lanes are maintained, but road users do not necessarily follow the lane-following pattern, may not always promise the implementation of a good leader-follower model. One such project in India is Pradhan Mantri Gram Sadak Yojana (PMGSY), which was started in 2000 to connect rural areas with other major roads such as NH and SH to provide easy access for residents to sell and purchase their goods. The project has also improved the standard of living of people by making them more accessible to NH and SH. PMGSY covers the streets of different areas (ODR) and town streets (VR) that have a single path street for two-way traffic, playing a crucial role in connecting rural areas to market communities, the base camp of Taluka, the improvement center of the block, or other primary roads [40]. Although several studies have examined the performance of different roads, such as NH and SH, in terms of service level (LOS), no such examination has been carried out for single-path roads [40]. A road is considered to have good LOS when vehicles travel at their optimal speed or in free flow conditions (FFC), which refers to the condition in which vehicles travel at their ideal speed without being influenced by other vehicle classifications in the same traffic flow [40]. Studies presume that a vehicle should travel in free flow conditions if its speed is not affected by any other vehicle in the traffic flow [40].

4.3 RD3: optimal infrastructure design

Efficient models that estimate the capacity of current and future road infrastructure in developing countries do not address the question of optimal design of such infrastructure. To address this gap, ongoing research is focused on determining the ideal infrastructure configuration in terms of routes, geometry, and signage, while taking into account the unique characteristics of developing countries, such as specific driver behaviors, heterogeneous traffic, and an existing infrastructure that contains many roundabouts and unsignalized intersections.

Investing in technology and infrastructure for the transportation industry requires considering various factors. Developing countries face challenges due to the lack of categorization of land parcels and mixed land use. This leads to the need for new or modified road sections and the interference of heavy and light vehicles on urban roads. This point of view is shared by Kumar et al. [125] and Outay et al. [17]. They highlight a major research challenge related to the requirement of cyber infrastructure. In fact, it constitutes one of the main barriers to the adoption of self-driving vehicles, especially in developing countries. These changes affect (self) driving behavior and can lead to longer commutes and a dangerous impact on drivers.

This research study emphasizes the need to understand the land parcels, comply with the required road standards, and consider the environmental impacts and energy consumption. Researchers should focus on the patterns of following new cars to address the impact of these changes on drivers.

Some researchers try to overcome the problem of the existence of a cyber infrastructure by allowing vehicles, and especially autonomous vehicles, to interact directly without information from the cyber infrastructure. For example, [127] onsidered that intersections are major bottlenecks for road traffic, as well as the source of many accidents. They propose an inter-vehicle scheduling algorithm for intersections of cooperative vehicles in order to maximize the throughput of the intersection. More specifically, they propose an approach based on deep reinforcement learning and Markov Decision Process to efficiently distribute the right-of-way to each vehicle.

5 Related works

The focus of this research is specific. However, several articles have been published, which provides survey articles related to the topics of this article. This section provides a brief overview of these secondary studies.

Cidjeu Djeuthie et al. [128] have conducted a short survey with research questions similar to those presented in this article. However, they have focused their study on sub-Saharan countries, when our study has no geographical limitation. There are some similarities in the terminology used, such as the application of multiagent models for spatiotemporal dynamic growth in developing urban areas; the literature does not address the specific focus of this research [129]. For example, previous research on the modeling of driver route choice does not consider the dynamic and virtual infrastructure [130]. The latter study aims to demonstrate the ability to make environmental decisions with the support of travel information that does not align with the point of interest in this research. In the articles of Bouhsissin et al. [131] and Zaidan et al. [132], the aim of the study is to highlight and analyze the different types of driver behavior, data sources, datasets, characteristics, and artificial intelligence techniques used to classify driver behavior and its performance. Both of these secondary studies do not focus on developing countries and the associated issues. Elamrani Abou Elassad et al. [133] presented an SLR of the concept of driving behavior with a holistic approach to the different aspects of driving behavior analysis, as well as a scheme to guide the future development and implementation of assessment strategies. In the second part of this article, an overview of the literature on machine learning is highlighted. Saleh et al. [134] provided an SLR on the development of sustainable heritage cities in Malaysia without focusing on mobility and driving models. Among the secondary studies found by the authors, none is dedicated to agent-based modeling of traffic and drivers.

Regarding the SLR methodology, many secondary studies have been published using this approach. Tchappi et al. [135] have proposed an SLR study on the usage and application of holonic multiagent systems in the fields of traffic and transportation. Mualla et al. [136] have provided a very detailed survey on the modeling and application of drones in civilian applications. Mkhinini et al. [137] provided a comprehensive review of the combination of the Unified Modeling Language and ontology paradigm. Calvaresi et al. [138] were interested in the design of chatbots with an individual perspective and using the agent-oriented modeling paradigm.

6 Conclusion

In this research, the survey of behavior models for drivers in developing countries has been extensively studied, with various ideologies and concepts captured to help understand the subject matter. The study identified that driver psychosocial behavior plays an important role in altering or improving the road environment with its associated interactors. Various car follower models that are currently adopted or exist in many developing countries were discussed, evaluated, and reviewed. The report also identified various properties that must be considered to adapt a driver model, especially with unsteady traffic flows, excessive approach demand, and varying directional flows at roundabouts. The traffic operations and congestion design process adopted in certain cities in Asia and Africa were very useful to predict and determine the importance of geometric standards on roads, which can play a vital role for any driver behavior model when deployed and tested.

The model analyzes indicated that the behavior of drivers in developing countries is more hazardous, or they do not adhere somewhat to the traffic rules. Prompt suggestions based on the overall study would be to recommend the future scope of research on traffic environments in countries such as India, the Philippines, Thailand, and parts of Africa. An unprecedented scenario-based driver behavior model is already available for highly developed countries. Coverage of car following models during adverse climatic conditions would help identify potential risks and threats faced by drivers and their behavioral condition, which can become a source of information to build future concepts on Lane following models. On this note, if such an initiative takes place, the level of scope of such models can be assessed and recommended to other developing countries.

To the researcher's knowledge and awareness, no literature articles are available that summarize and capture the developing country's driving behavior models in one research study. Thus, this research work can benefit future scholars and researchers in identifying this as a basis for further extension. It is essential to note that this research study did not explicitly point out a particular driving behavior model of interest, but it captures the essence of various prevalent car following models and driver behavior models associated with developing countries.

Author contributions

VAG has completed the SLR process as a Master student. He is also the main contributor to the text of the article. SG has realized the SLR process as an expert. He is also the second major contributor to the text of the article. He is the major contributor for the revised text of the article. AL has performed the SLR process as an expert. He is also the third major contributor to the text of the article. TM has performed the SLR process as an expert. He is also the fourth major contributor to the text of the article. NG, HZ, and A-U-HY have played the role of additional expert and referee. And they have improved the sections on analysis and research questions. All authors read and approved the final manuscript.

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Data available on demand.

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