“To Lane or Not to Lane?” - Comparing On-Road Experiences in Developing and Developed Countries using a New Simulator *RoadBird*

Md. Masum Mushfiq*, Tarik Reza Toha†, Saiful Islam Salim‡, Aaiyeesha Mostak§, Masfiqur Rahaman¶, Najla Abdulrahman Al-Nabhan‖, Arif Mohaimin Sadri**, and A. B. M. Alim Al Islam††
*†‡§¶††Department of CSE, Bangladesh University of Engineering and Technology, Dhaka, Bangladesh
‖Department of CS, King Saud University, Riyadh, Saudi Arabia
**School of Civil Engineering and Environmental Sciences, University of Oklahoma, Norman, OK-73019, USA
Email: *masummushfiq@cse.buet.ac.bd, †1017052013@grad.cse.buet.ac.bd, ‡1018052067@grad.cse.buet.ac.bd, §0419052029@grad.cse.buet.ac.bd, ¶1505111.mr@ugrad.cse.buet.ac.bd, ‖nalnabhan@ksu.edu.sa, **sadri@ou.edu, ††alim_razi@cse.buet.ac.bd

***Abstract*—Even though the traffic systems in developed countries have been analyzed with rigor and operated efficiently, the same does not generally hold for developing countries due to inadequate planning, design, and operations of their transportation systems. Because of inherent differences between internal infrastructures, the strategies deployed in developed countries may not be amenable to developing ones. Besides, developing countries' traffic systems are not well-studied in the literature to the best of our knowledge. For example, it is yet to explore how a developed country's lane-based traffic flow would perform in the context of a developing country, which generally experiences non-lane-based traffic. As such, by using our newly developed traffic simulator 'RoadBird,' we investigate outcomes of both lane-based and non-lane-based traffic from the contexts of both developing and developed countries. To do so, we run simulations over real road topologies (extracted from the GIS maps of major cities such as Dhaka, Miami, and Riyadh) considering different scenarios such as lane-based or non-lane-based flows, homogeneous or heterogeneous traffic, with or without pedestrians, etc. We also incorporate different car-following and lane-changing models to mimic traffic behaviors and investigate their performances. While the lane changing dilemma remains an open research question, our experimental evidence indicates: (i) lane-based approaches will not necessarily perform better in the case of currently-adopted non-lane-based scenarios, and (ii) non-lane-based strategies may benefit system performance in lane-based scenarios while having heavy mixed traffic. Nonetheless, we reveal several new insights for on-road experiences both in developing and developed countries.**

I. Introduction and Motivation

DHAKA, the capital of Bangladesh, is one of the megacities of the world. However, the chaotic traffic system of Dhaka is a major headache for the city dwellers. Traffic congestion in Dhaka is responsible for wasting around 3.2 million working hours daily, costing the economy billions of dollars [1]. In this condition, saving even a single minute on average can save millions of dollars. Traffic simulation software is a useful tool for system-wide traffic impact assessment and sustainable policy making that can come into play in cases such as Dhaka. This can be done by testing the impact of a proposed policy on the intended traffic network. However, the effectiveness and applicability greatly vary with how accurately the simulator can mimic the desired traffic stream. As Dhaka is a city of unstructured (non-lane based) heterogeneous (high mix of slow and faster-moving vehicles) traffic, its traffic stream experiences diversified on-road scenarios such as pedestrian on road, illegal parking, deliberate rule violation, jaywalking, and so forth. These are quite different from the structured (lane-based) traffic systems of developed countries with homogeneous traffic in terms of speed. Existing traffic simulators lack the ability to accommodate such on-road scenarios. Hence, the need for an advanced simulator with more customized features comes into play for simulating both structured and unstructured traffic behaviors.

As already pointed, vehicles not following lanes are among the significant attributes of Dhaka city's traffic. On the contrary, the traffic stream is mostly lane-based in the major cities of developed countries. Therefore, it is quite natural for the following question to arise: ”What would happen if Dhaka's traffic system is converted into a lane-based system?” Likewise, what would happen if the major cities in developed countries adapt to non-lane-based strategies? In this study, we investigate this dilemma between ”to lane or not to lane” to decide on better system performance. To the best of our knowledge, such a study is yet to be done in the literature, and we are the first to do so.

In our study, we have developed a new microscopic traffic simulator named RoadBird, based on its earlier version, formerly called DhakaSim [2]. In our current work, we extend the simulator to simulate both lane-based and non-lane-based traffic and incorporate different traffic behavioral phenomena such as car-following and lane-changing models to mimic realistic traffic behavior. We investigate their performance and choose the best applicable model for further experimentations. RoadBird can also simulate actions of other traffic entities such as pedestrians, slow vehicles (i.e., rickshaw), bikes, etc. In this study, we run simulations on topologies extracted from Dhaka, Miami, and Riyadh's GIS maps to analyze their performances and trajectories. After that, we use different performance metrics to measure performances in different scenarios.

Based on our work, our contributions are as follows:

- We present a new traffic simulator RoadBird, which is capable of simulating both lane-based and non-lane-based traffic in the presence of both homogeneous and heterogeneous traffic streams. RoadBird can also take account of diversified scenarios experienced over roads in developing countries like pedestrians on the street, movement of slow vehicles such as rickshaws, etc.
- We simulate RoadBird to compare the performances in both developed and developing countries by varying traffic load on the network from low to high vehicle generation rate and by varying the ratio of different vehicle types, i.e., the vehicular mix. Here, we use the road networks extracted from Miami and Riyadh as representatives of developed country's road network, and the road network extracted from Dhaka as a representative of developing country's road network.
- Our observations further analyze and show that non-lane-based systems exhibit better performance by utilizing the road space more efficiently with heterogeneous traffic and narrow roads. However, with homogeneous traffic and wide streets, lane-based systems exhibit better vehicles' speed and flow rate.
- While lane-based approaches will not necessarily yield more efficient outcomes in non-lane-based scenarios, the other side of the coin is not this impotent. This happens as non-lane-based strategies may benefit system performance in lane-based scenarios with heavy mixed traffic, which we confirm by our analysis.

II. Background and Related Work

Life in Dhaka is difficult due to its chaotic traffic condition. Microscopic traffic simulation is widely used and one of the most effective ways to predict traffic behavior. These tools can aid in taking important transportation engineering decisions by simulating the proposed decisions and analyzing its impact on the existing traffic network. However, its effectiveness greatly depends on the accuracy of mimicking the intended traffic pattern. Although there exist several microscopic traffic simulators in the literature, they fail to mimic the non-lane-based heterogeneous, i.e., unstructured traffic stream of Dhaka city. Hence, we need a customized traffic simulator to simulate the impact of a transportation engineering policy on an unstructured traffic stream. In our previous work, we have developed a non-lane-based traffic simulator named as DhakaSim [2] to simulate the diversified behavior of traffic. However, it lacks the capability of simulating a lane-based structured traffic stream. Moreover, no comparative study between lane-based and non-lane-based heterogeneous traffic performance has been done. Hence, we extend the existing DhakaSim traffic simulator to RoadBird to simulate both lane-based and non-lane-based traffic streams and conduct an extensive experimental study to derive a conclusive remark about "To lane or not to lane". Next, we present some existing work on heterogeneous traffic simulations and related models.

Vedagiri et al., [3] propose a simulator named HETEROSIM to simulate heterogeneous traffic flow considering Indian road traffic. They estimate the saturation flow rate of heterogeneous traffic considering the effect of road. From the simulation result, they have found a linear relationship between saturation flow and road width. Arsasan et al., [4] measure one of the fundamental characteristics of traffic flow, i.e., concentration using HETEROSIM. They argue that the traditional concept of concentration cannot be applied to heterogeneous and non-lane-based traffic and propose a new concept named as area-occupancy to measure traffic concentration for heterogeneous and non-lane-based traffic.

There are few studies about modeling heterogeneous traffic flow. Arasan et al., [4] propose a simulation framework for the traffic-flow model where the absence of lane discipline in mixed traffic flow conditions is taken into account. They also describe common issues related to traffic simulation in the context of heterogeneous traffic conditions. Olstam et al., [5] discuss a different car-following model only for lane-based traffic. Jin et al., [6] propose a non-lane based full velocity difference car-following model where they incorporate the lane width effect in car-following models and show that lateral separation effect greatly enhances the realism of non-lane based car-following models. Muniruzzaman et al., [7] propose a method to calibrate and validate non-lane based microscopic simulation models, however, they do not compare between lane-based and non-lane based traffic systems.

Mathew et al., [8] propose a space discretization–based simulation framework named as SiMTraM to address the driver behavioral models in the heterogeneous traffic stream. This simulator can simulate both the lane-based and non-lane-based traffic. However, the proposed simulator has no implementation for the random movement of the pedestrians and non-motorized traffic on the road. Agarwal et al., [9] propose an agent-based framework, that uses a queuing model to simulate the mobility of only motorized vehicles. Mohan et al., [10] propose a parsimonious model of heterogeneous traffic that can capture the unique phenomena of the gap-filling behavior of vehicles. They have calibrated and validated the model using field data from an arterial road in Chennai city. Chand et al., [11] develop a dynamic PCU for the candidate signalized intersections catering to mixed traffic conditions in Indian cities. However, the proposed simulator does not deal with random movement of the pedestrians and non-motorized traffic on the road.

All of the aforementioned studies explore different aspects of lane-based structured traffic. However, a comparative study between the lane and non-lane-based traffic with heterogeneous motorized and non-motorized traffic stream is yet to be done. Hence, we perform comparative study among structured and unstructured traffic through our custom designed and developed simulation software named as RoadBird in this work. Next, we present the methodology of our study.

III. Overview of Our Study

In our study, first we implement some prominent car-following and lane-changing models from existing study. We also customize some of the models to better fit the heterogeneous nature of the traffic flow. We investigate over these models through simulation and choose the best fitting model. Then using the chosen models, we compare the performance of lane-based and non-lane-based road networks. We present the flowchart of our comparative study in Figure 1.

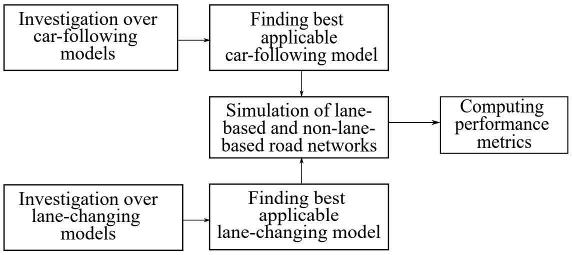


Fig. 1: Flowchart of our comparative study

A. Car-Following Models

In our study, we implement three different car-following models and compare the performance by varying these models. Next, we describe each of them.

1) Newtonian Car-Following Model with Hard Braking: In this model, the following equations are used to compute the speed, distance, and acceleration of a vehicle.

$$\Delta x = x_{n-1}(t) - s_{n-1} - x_n(t) \tag{1}$$

$$v_n(t+\tau) = \begin{cases} v_n + a_n\tau, & \text{accelerating} \\ \frac{\Delta x}{\tau}, & \text{braking} \end{cases} \tag{2}$$

$$x_n(t+\tau) = x_n(t) + v(t)\tau \tag{3}$$

$$a_n(t+\tau) = a \tag{4}$$

where Δx is the safe distance between leader and subject vehicle, τ is the time step which is $1s$ for our simulation, s_{n-1} is the effective length of the subject vehicle, $x_{n-1}(t)$ and $x_n(t)$ are the distance of the leading vehicle $n-1$ and subject vehicle n in a link.

2) Gipp's Car-Following Model: In the second model, distance and acceleration is calculated as the Newtonian model. However, speed is calculated according to Gipp's model [12] as shown in Equation 5.

$$v_n(t+\tau) = min \begin{cases} v_n(t) + 2.5a_n\tau(1 - \frac{v_n(t)}{v_n^d})\sqrt{0.025 + \frac{v_n(t)}{v_n^d}} \\ b_n\tau + \sqrt{b_n^2\tau^2 - b_n[2(\Delta x) - v_n(t)\tau - \frac{v_{n-1}(t)^2}{b}]} \end{cases} \tag{5}$$

Where τ is the reaction time; $v_n(t)$ and $v_{n-1}(t)$ are the speed of the subject vehicle n and the leading vehicle $n-1$ at time step t, respectively; v_n^d is the vehicle n desired speed; a_n is the vehicle n maximum acceleration; b_n and b are the most severe braking that the driver of vehicle n wishes to undertake and the expected leading vehicle maximum deceleration, respectively. Here no explicit braking is applied. So vehicles collide with each other.

3) Hybrid Model: Hybrid model is the combination of the previous two models. In this model, vehicles normally move with speed from Gipps' model 5, however, if they are about to collide, braking is applied using 3.

B. Discretionary Lane Changing Models

Discretionary lane changing (DLC) models have three parts-desire to change the current lane, ensure changing lane is feasible, and decision to change lane based on gap acceptance. We implement three DLC models in our simulation. Next, we describe each of them.

1) Straight-forward Model: In this model, when a vehicle cannot move forward or has a slower leader in proximity, it wants to change its lane. If its target lane has enough space to accommodate it, it just shifts to the target lane.

2) Gipp's Model: In the Gipps' model, we first compute the braking of the subject vehicle using Equation 6.

$$b_n(t) = v_n(t-1) - v_n(t) \tag{6}$$

$v_n(t-1)$ and $v_n(t)$ are computed using Gipp's formula from equation 5 where subject is vehicle n and target leader is vehicle $n-1$. Similarly, the braking of the target follower is computed using Equation 6, where the target follower is vehicle n and subject is vehicle $n-1$. Now, if computed braking of the subject and the target follower is lower than their maximum desired braking, lane change is feasible. Gap acceptance probability is calculated using Equation 7.

$$p(t) = \begin{cases} 1 - e^{-\lambda(t-T)}, & \text{t > T} \\ 0, & \text{otherwise} \end{cases} \tag{7}$$

where, λ is a co-efficient, T is the critical time gap, t is the actual time gap which can be computed as, $t = \frac{g}{v_n}$. Here, g is the lead/lag gap, v_n is the speed. The probability that we accept the gap is the product of the probability of both the lead and lag gap are accepted, that is,

$$p(t^{lead}, t^{lag}) = p(t^{lead}) \times p(t^{lag}) \tag{8}$$

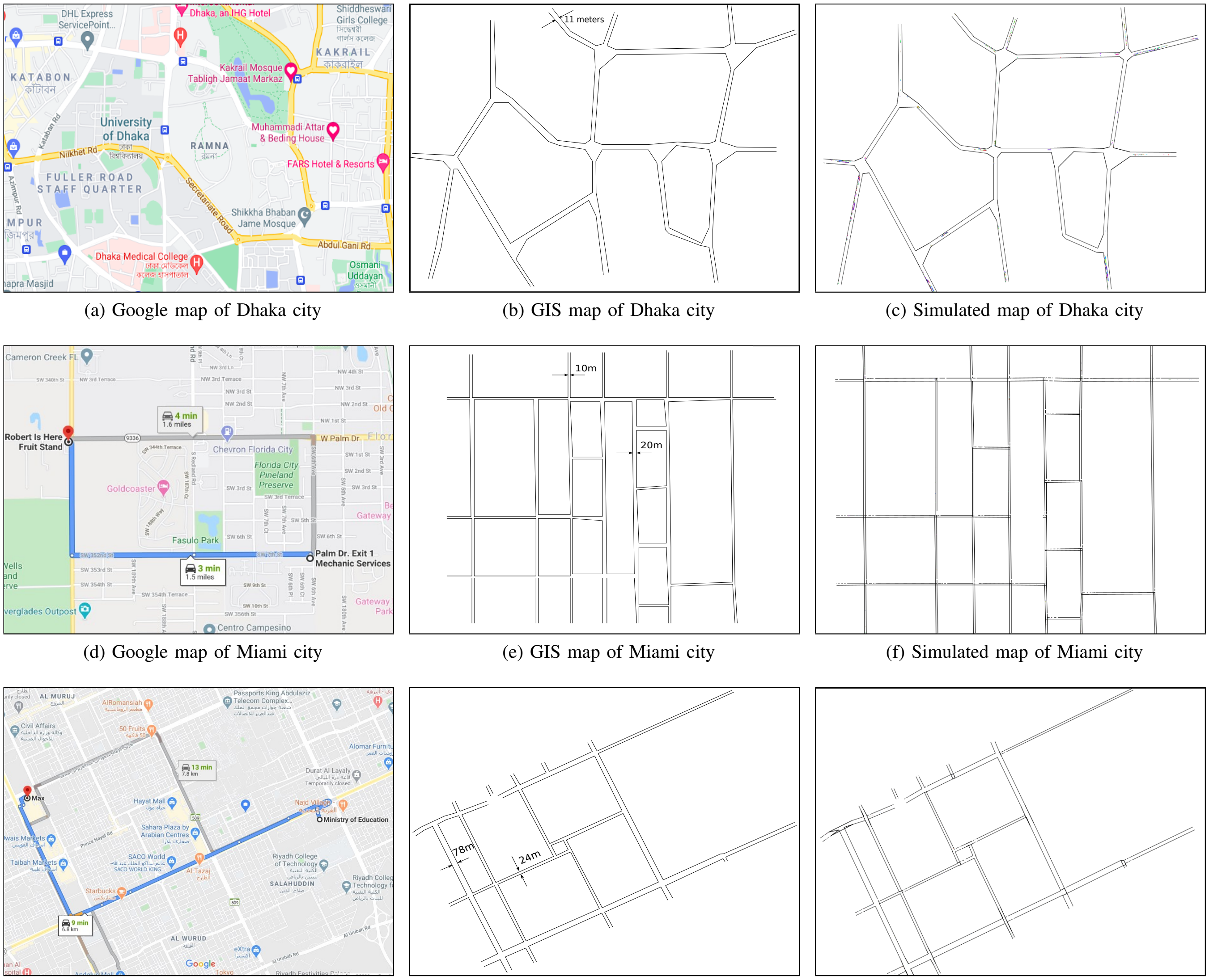
3) GHR Model: In the GHR model, acceleration is used to decide whether to change a lane or not. This acceleration is computed using GHR [13] equation as follows,

$$a_n(t) = cv_n^m(t)\frac{\Delta v(t-T)}{\Delta x^l(t-T)} \tag{9}$$

where, a_n is the acceleration of vehicle n implemented at time t by a driver and is proportional to, v_n the speed of the nth vehicle, Δv and Δx are the speed and space spacing between the leader and subject vehicle. c is the sensitivity co-efficient; m is the speed exponent (-2 to +2), l is the distance headway exponent (+4 to -1). We use $c = 15$, $m = 1$, and $l = 2$ for our simulation. Now, in the first step, if $a_n < 0$, the subject vehicle wishes to change the lane. Then, braking is computed using Equation 9, however, lane changing and gap acceptance decisions are taken similarly as Gipps' lane changing model.

C. Vehicle Generation Model

The vehicles are generated according to the negative exponential distributions of vehicular headways. The probability density function is computed by $f(x) = \lambda e^{-\lambda x}$ and the expression for exponential variate headway X can be derived as $X = \mu(-\ln R)$, where μ is the mean headway, R is the random number between 0 and 1.



(a) Google map of Dhaka city (b) GIS map of Dhaka city (c) Simulated map of Dhaka city

(d) Google map of Miami city (e) GIS map of Miami city (f) Simulated map of Miami city

(g) Google map of Riyadh city (h) GIS map of Riyadh city (i) Simulated map of Riyadh City

Fig. 2: Simulation environment and topologies used in our simulations

D. Both Lane and Non-lane Based Traffic Simulation

In our work, a link is composed of a number of strips. The width of the strips is a parameter of the simulator. The number of strips on a link is calculated as follows,

$$\#\ of\ strips = \left\lfloor \frac{link\_width}{strip\_width} \right\rfloor$$

Each vehicle occupies some strips according to its width, computed as follows,

$$\#\ of\ occupied\ strips = \left\lceil \frac{vehicle\_width}{strip\_width} \right\rceil$$

Now, if the strip width is greater than the width of a vehicle, the vehicle will be fully contained in a single strip and that single strip can be considered as a lane. Thus, by varying the strip width, we simulate both lane and non-lane-based traffic.

E. Performance Metrics

To compute the overall performance of a road network under different parameters, we use four performance metrics- average speed on a link, average waiting time on a link, average vehicle flow rate of a link, and average speed of a vehicle [14]. Now, we describe each of the performance metrics.

1) Average speed on a link ($\overline{speed_{l_i}} km/hour$): This metric represents the speed with which a vehicle typically crosses the corresponding link and is calculated for all links using Equation 11. Higher speed indicates better performance.

$$\overline{speed_{v_l}} = \frac{length_l}{\overline{time\_to\_cross_l}} \tag{10}$$

$$\overline{speed_l} = \frac{\sum_{v \in S_l} \overline{speed_{v_l}}}{|S_l|} \tag{11}$$

TABLE I: Vehicle generation distribution

Speed category	Vehicle type	Vehicular modal share (%)	Vehicle distribution (%) Dhaka	Vehicle distribution (%) Miami and Riyadh
Slow vehicles	Bicycle	9%	55	9
	Rickshaw	89%		
	Van/Cart	2%		
Medium vehicles	CNG	83%	40	75
	Bus (2 types)	15%		
	Truck (2 types)	2%		
Fast vehicles	Motorbike	88%	5	16
	Car (3 types)	12%		

TABLE II: Simulation parameters for validation

Simulation time (minutes)	40	Vehicle generation rate (vehicle/hour)	Low traffic density	100
# of iterations in each case	15		Medium traffic density	400
# of intersections	8		High traffic density	800
# of vehicle generating nodes	8	Pedestrian mode		On
# of links	18	Strip width (m)		0.5
Distance between the two destinations (km)				4.3

where, $\overline{speed_v}$ is the average speed of vehicle v on link l and S_l is the set of all vehicles that crosses link l.

2) Average waiting time on a link ($\overline{t_l}s$): This metric indicates the average time a vehicle has to wait without movement in a link. It is calculated for all links using Equation 12. Lower average waiting time indicates better performance.

$$\overline{t_l} = \frac{\sum_{v=1}^{N} waiting\_time_v}{N} \tag{12}$$

where $waiting\_time_v$ is the individual waiting time of vehicle v while crossing link l and N is the total number of vehicles that leave link l.

3) Average vehicle flow rate of a link (vehicle/hour): This metric indicates the flow rate of a link and is calculated as the average number of vehicles that cross the middle of the corresponding link in an hour. The higher the better for this metric.

4) Average speed of vehicle ($\overline{speed_v} km/hour$): This metric represents the speed with which a vehicle travels and is calculated for all vehicles using Equation 14. Higher average vehicle speed indicates better performance.

$$\overline{speed_i} = \frac{total\_distance\_traveled_i}{total\_travel\_time_i} \tag{13}$$

$$\overline{speed_V} = \frac{\sum_{v \in S_v} \overline{speed_v}}{|S_v|} \tag{14}$$

where, S_v is the set of all vehicles, $\overline{speed_i}$ is the average speed of the vehicle i, and $|S_v|$ is the total number of vehicles.

IV. Experimental Setup

In this section, we describe the experimental setup of our comparative study.

We vary a number of significant parameters of our simulator and gather data through simulations for further exploration and performance comparison among lane-based and non-lane-based road network. We conduct traffic simulation for 1800 s or half an hour for each sample and generate 10 samples using random number seed 1-10 for each scenario and take the average of the 10 samples for generating graphs and analyzing our result. We can give different road topology as input to our simulator. We use three road topologies extracted from the GIS map. They are parts of Dhaka, Miami, and Riyadh city shown in Figure 2. We have three different vehicle generation rates: low, medium, and high. We have three types of vehicles: slow human-powered vehicles (max speed $\leq$ 15 km/hour), vehicles with medium speed (30 km/hour $\leq$ max speed $\leq$ km/hour), and fast vehicles (80 km/hour $\leq$ max speed $\leq$ 120 km/hour). We use 100, 400, and 800 vehicle/hour as low, medium, and high generation rate for Dhaka topology, respectively. On the other hand, we use 500, 1000, 2000 vehicle/hour as low, medium, and high generation rate respectively for Miami and Riyadh topologies. This parameter is used to simulate lane-based or non-lane-based traffic behavior. We use 0.5 m and 2.5 m as strip width to simulate non-lane and lane-based road traffic respectively. We can enable/disable the irregular crossing of roads by pedestrians by the Pedestrian Mode parameter. Properties and distribution of vehicles used in the simulations are shown in Table I.

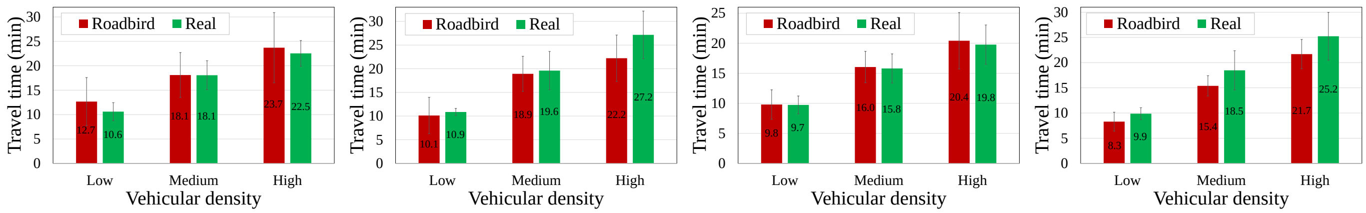
V. Validation of RoadBird

Validation is an integral part of ensuring the credibility of a simulator, as it checks how accurately the simulator represents the real world. Accordingly, we perform validation of outcomes of RoadBird in comparison to real-world cases.

A. Data Collection for Validation

In the process of our validation, we choose travel time as a measure of effectiveness (MOE). To measure the travel time, we select a route in the Dhaka city from Shankar to Palashi. To get real travel times on the selected route over several periods, we collect travel time data in both directions over the route for two types of vehicles namely cars and motorbikes. In the process of collecting travel time data, we log real-time travel times from Google Map, as it provides live travel time. Besides, we have extracted the selected route from the GIS map to run our simulations in RoadBird. We perform several iterations over the simulator and collect outcomes.

We use three different vehicle generation rates in our simulator. Besides, we divide the whole duration of a day (24 hours) into three parts based on on-road traffic density based on our day to day experience - 1) 10:00 PM - 09:00 AM for low traffic density, 2) 09:00 AM - 04:00 PM for medium traffic density, and 3) 04:00 PM - 10:00 PM for high traffic density. We have collected 63 real travel data from the Google Map in total over these durations in recent times. We do not use travel time data during the pandemic period when the lockdown period is in operation due to COVID-19, as traffic density is substantially less than usual during this period. Out of the 63-travel data from Google Map, we have collected 34 data during the pre-Corona pandemic age and the rest are during the Corona pandemic age. We have used some data from the Corona pandemic age as these data are applicable



(a) Shankar to Palashi with car (b) Palashi to Shankar with car (c) Shankar to Palashi with motorbike (d) Palashi to Shankar with motorbike

Fig. 3: Travel time comparison between observed and simulated data for car and motor-bike in Shankar to Palashi route

TABLE III: Summary result for t-test and error computation

Route	Shankar to Palashi						Palashi to Shankar					
Vehicle type	Car			Motorbike			Car			Motorbike		
Vehicle density	Low	Medium	High	Low	Medium	High	Low	Medium	High	Low	Medium	High
p-value of t-test	0.281	0.134	0.69	0.009	0.381	0.802	0.637	0.242	0.12	0.62	0.021	0.018
p-value of K-S test	0.375	0.181	0.375	0.009	0.626	0.925	0.003	0.181	0.181	0.375	0.076	0.009
ME (min)	-1.261	-2.325	-0.712	1.581	-0.894	-0.318	0.447	1.861	2.842	-0.459	2.907	4.403
MAE (min)	2.046	2.359	3.36	1.581	0.898	0.931	1.858	2.217	3.248	1.349	2.907	4.576
RMSE (min)	2.753	3.214	3.78	1.659	1.152	1.337	2.99	2.464	3.875	2.315	3.352	5.078
MAPE (%)	18.333	11.933	15.153	16.64	5.32	5.533	16.84	11.367	11.233	12.467	14.547	17.327
RMSPE (%)	24.199	15.314	17.38	17.611	6.476	8.692	25.72	12.811	12.994	19.78	16.056	18.353

for low and medium traffic density. However, we collect high traffic density data only from the pre-Corona pandemic age.

Besides, in case of our simulations, we collect travel times from 45 iterations in total, where we consider 15 iterations for each of the three different traffic density cases. Table II presents our simulation parameters.

B. Performance Comparison

We present our simulation results in Figure 3. Here, Figure 3a and 3b present average travel times of cars under low, medium, and high traffic density in both directions of the selected route. Besides, Figure 3c and 3d present average travel times of motorbikes under low, medium, and high traffic density in both directions of the selected route. Results presented in Figure 3 show that travel times obtained through simulations of RoadBird and obtained in real scenarios closely match with each other. To further dig into how far they match each other, we perform several statistical analyses over the travel time data which are discussed in the following sections.

C. Statistical Analysis over Real and Simulated Outcomes

For statistical validation, we consider a two-sample t-test and Kolmogorov-Smirnov (K-S) test with a 5% level of significance [15]. The null hypothesis in these tests is that the travel time observed from the real world and the travel time computed by our simulator come from the same distribution, and the alternative hypothesis is they come from different distributions. Then we compute the p-value. From the p-value, we can estimate how closely the simulation matches the real world. Goodness-of-fit measures are generally used to compute the overall performance of simulation models. According to Toledo et al., [16], Ni et al., [17], popular goodness-of-fit measures are, Mean Error (ME), Mean Absolute Error (MAE), Root Mean Square Error (RMSE), Mean Absolute Percentage Error (MAPE), and Root Mean Square Percentage Error (RMSPE), etc. We can quantify the overall error of our simulator with these statistics. So, we have computed these statistics and the results are summarized in Table 3.

D. Qualitative outcomes of our statistical analysis

From the p-value of both of our two-sample t-test and two-sample K-S test, with a 5% level of significance, we can see that in 9 out of 12 cases, we have p-value greater than our chosen LOS which clearly states that our simulation closely matches the real-world traffic scenario. Mean Error (ME) indicates the existence of systematic under- or over-prediction in the simulated measurements. From our calculation, we can say that our simulator is not inherently biased in any direction. From Mean Absolute Error (MAE) and Root Mean Square Error (RMSE), we can say that our predicted travel time varies from less than 1 minute to at most 5 minutes. From Mean Absolute Percentage Error (MAPE), we can say that the accuracy of our simulator varies from 82-95% with an average accuracy of 88%. From Root Mean Square Percentage Error (RMSPE), we find that the average accuracy of our simulator is 85% with a peak value of 94%. Though RMSPE penalizes the outliers more, we have only two cases where the accuracy drops to 75%.

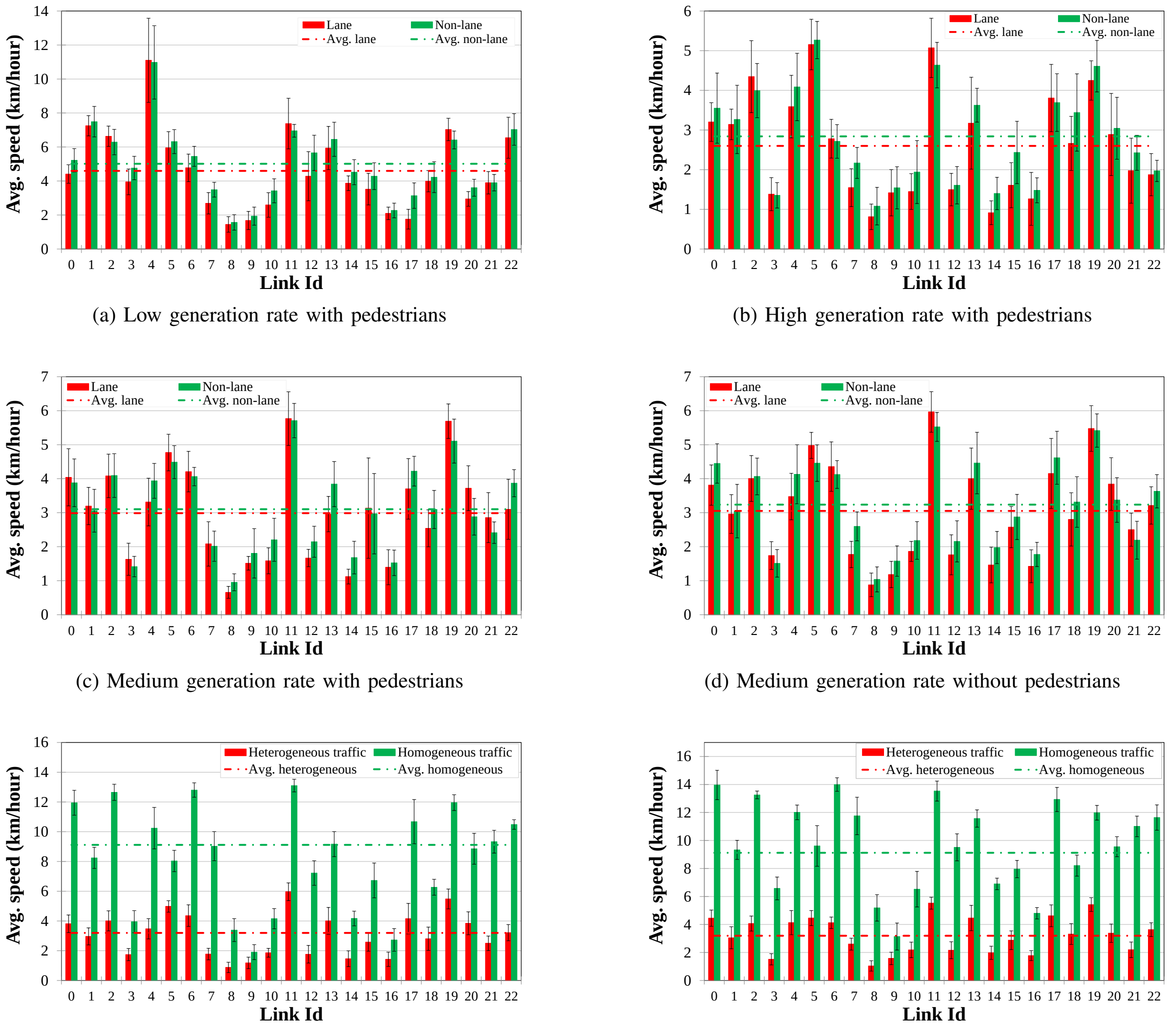
VI. Results

After validating our simulator, we simulate lane-based and non-lane-based traffic systems with the parameters described in the experimental setup part. Now, we present their comparative performance concerning different metrics.

A. Performance Comparison for Dhaka Topology

As a representative city of the developing world, we consider Dhaka to simulate both lane-based and non-lane-based traffic through varying different parameters of RoadBird. In the following subsections, we discuss the comparative performance of lane-based and non-lane-based traffic in Dhaka.

1) Performance comparison based on average speed on a link: We present performance comparison based on average speed on a link for Dhaka topology under various combinations in Figure 4a, 4b, 4c. According to this figure, the average speed on a link decreases with increasing vehicle



(a) Low generation rate with pedestrians

(b) High generation rate with pedestrians

(c) Medium generation rate with pedestrians

(d) Medium generation rate without pedestrians

(e) Lane-based network with medium generation rate

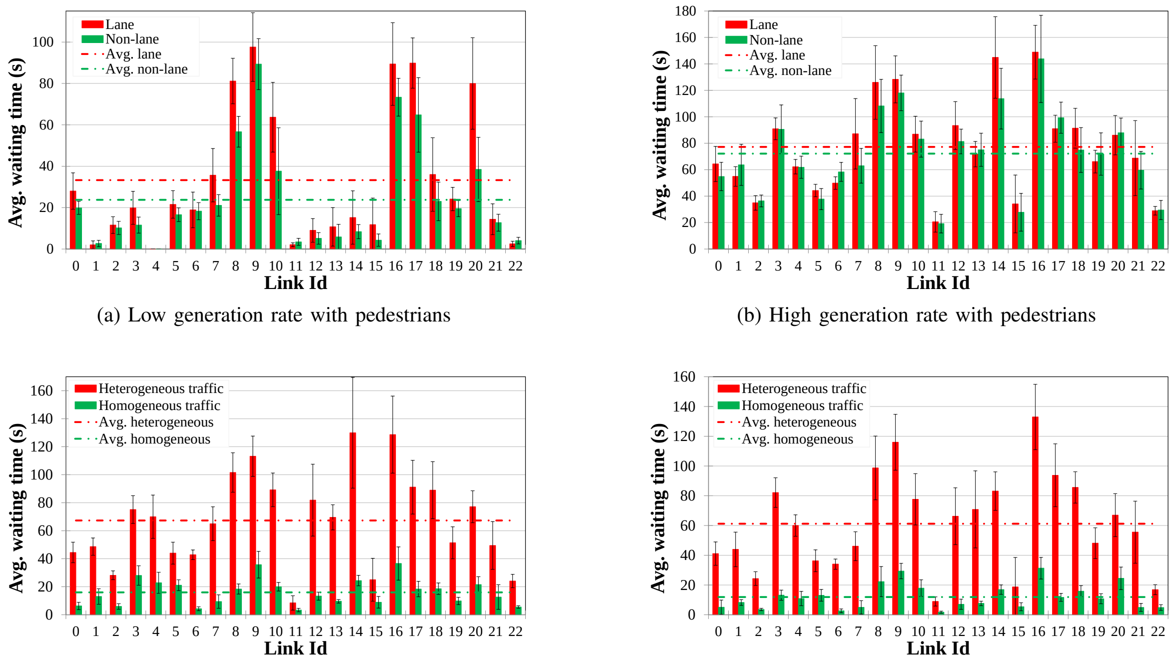
(f) Non-lane-based network with medium generation rate

Fig. 4: Performance comparison based on average speed on a link for Dhaka topology under various combinations

generation rate. Besides, the average speed on links is below 10 km/hour that matches the World Bank report [1], i.e., the average speed of Dhaka city is around 7 km/hour. We can also see that irrespective of generation rate, the average speed for the non-lane road network is higher than that of lane-based road networks. As roads of Dhaka are narrow and most of the vehicles are small such as rickshaw, motorbike, car, etc., non-lane-based systems better utilize the road space. Besides, as the traffic is heterogeneous and slow vehicles prevail in high ratios, speed is mainly controlled by the slow vehicles. This is the reason for the higher speed in the non-lane-based traffic stream. Here, we enable the pedestrians and adopt heterogeneous vehicle distribution as shown in Table I. If we compare the performance by keeping generation rate fixed to medium rate and enabling or disabling pedestrians on the road, the performance does not get changed significantly due to heterogeneous traffic which we can see in Figure 4c and 4d. If we compare the performance by changing the distribution of vehicles into homogeneous, performance significantly improves for both lane-based and non-lane-based traffic as slow vehicles are removed from the traffic stream which is clear from Figure 4e and 4f.

2) Performance comparison based on average waiting time on a link: We depict performance comparison based on average waiting time on a link for Dhaka topology under various combinations in Figure 5. According to this figure, average waiting time increases with the increase in vehicle generation rate and average non-lane waiting time is less than lane-based waiting time. If we change the traffic distribution into homogeneous, waiting on links significantly reduces.

3) Performance comparison based on average vehicle flow rate of a link: We present a performance comparison based on the average vehicle flow rate of a link in Figure 6a and 6b. From these figures, it is clear that the average vehicle flow rate increases with an increasing generation rate. Besides, the vehicle flow rate significantly increases for both lane-based and non-lane-based traffic networks when traffic distribution switches from heterogeneous to homogeneous as shown in Figure 6c and 6d.



(a) Low generation rate with pedestrians

(b) High generation rate with pedestrians

(c) Lane-based network with medium generation rate

(d) Non-lane-based network with medium generation rate

Fig. 5: Performance comparison based on average waiting time on a link for Dhaka topology under various combinations

4) Performance comparison based on the average speed of vehicle: We present the comparative performance based on the average speed of vehicles in Figure 6e and 6f. We can see that the average speed of vehicles decreases with the increase in vehicle generation rate. Besides, although non-lane-based networks perform better in low generation rate, lane-based networks outperform non-lane-based networks in high generation rate, which supports our practical experience. When the generation rate is high, the structured organization of lane-based traffic helps it to achieve better speed.

B. Performance Comparison for Miami Topology

In this subsection, we present the comparative study between Dhaka and Miami traffic systems through simulating lane-based and non-lane-based traffic on Miami topology. Although non-lane-based traffic cannot be seen in Miami city, Miami's traffic system becomes lane-less during a hurricane evacuation. Hence, we try to know what will happen if Dhaka's unstructured traffic runs in Miami. Next, we present the comparison based on the following performance metrics for lane and non-lane-based traffic in Miami topology.

1) Performance comparison based on average vehicle flow rate on the link: We depict average vehicle flow rates on links in Figure 7a. From the figure, it is clear that average vehicle flow rates for Dhaka distribution are higher than that of Miami distribution. The gap between the Dhaka traffic distribution and Miami traffic distribution becomes more prominent in case of the non-lane-based network (Figure 7a). Since most of the vehicles in Dhaka distribution are small and the roads of our chosen Miami topology are narrow as well, lane-less traffic maximizes road-space utilization, hence, it moves faster than structured traffic.

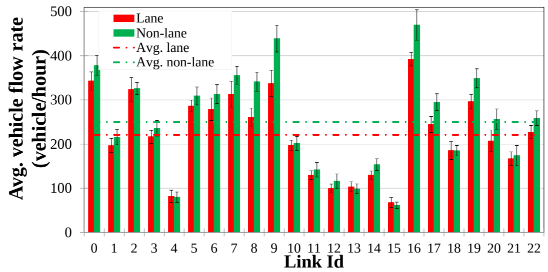
2) Performance comparison based on average waiting time on the link: Average waiting time on the link is shown in Figure 7b. From the figure, it is clear that Dhaka's traffic system experiences less waiting time than Miami's one which is more prominent in the lane-less network as before.

C. Performance Comparison for Riyadh Topology

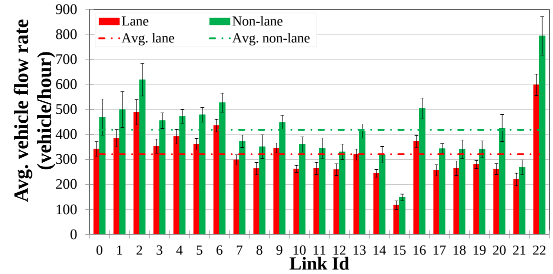
In this subsection, we compare performance between lane-based systems with homogeneous traffic and non-lane-based systems with heterogeneous traffic on Riyadh topology. Figure 8a and 8b show the performance comparison between Dhaka's traffic (lane-less) and Riyadh's traffic (lane-based). Unlike Miami, lane-based traffic performs better in Riyadh in both vehicle flow rate and waiting time. Since roads of Riyadh are much wider and longer than Dhaka roads as shown in Figure 2, it can accommodate a lane-based system better.

VII. Conclusions and Future Work

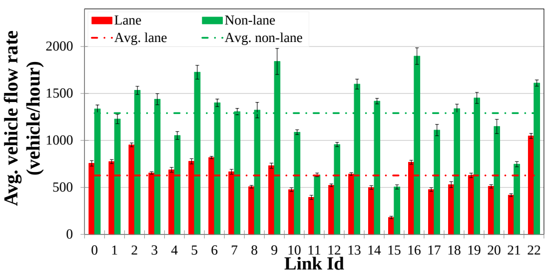
The current traffic system in developing countries is not as well-disciplined as the ones in developed countries. Hence, a comprehensive comparative study of these systems has not received much attention from the academic community. There has been a major gap in the literature in the above-mentioned contexts and existing studies do not address most of the major issues in these scenarios. In our work, we study extensively the dilemma of setting up hypothetically lane-based traffic systems in an existing non-lane-based setup. The average speed on links and vehicle flow rate on links decreases with increasing vehicle generation rate for both lane and non-lane-based systems. Waiting time on links increases with increasing vehicle generation rates for both lane and non-lane-based systems. Irregular road crossing by pedestrians do not significantly



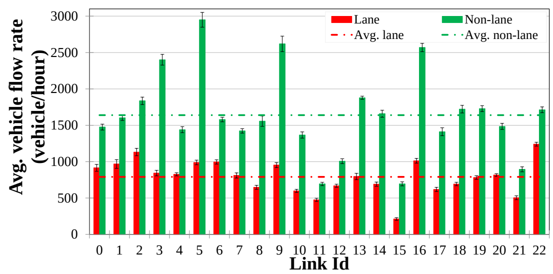
(a) Average vehicle flow rate in low generation rate with pedestrians



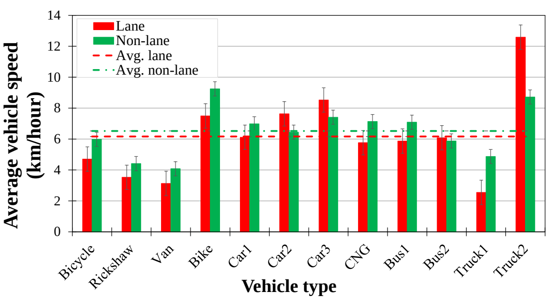
(b) Average vehicle flow rate in high generation rate with pedestrians



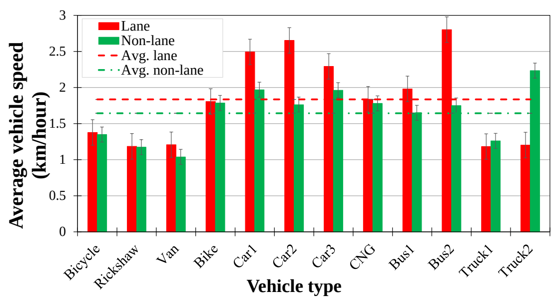
(c) Average vehicle flow rate in lane-based network with medium generation rate



(d) Average vehicle flow rate in non-lane-based network with medium generation rate

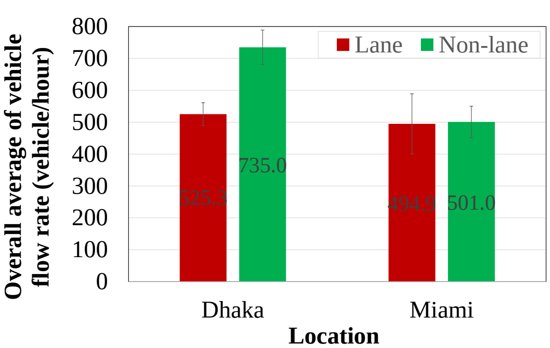


(e) Average speed of the vehicles in low generation rate with pedestrians

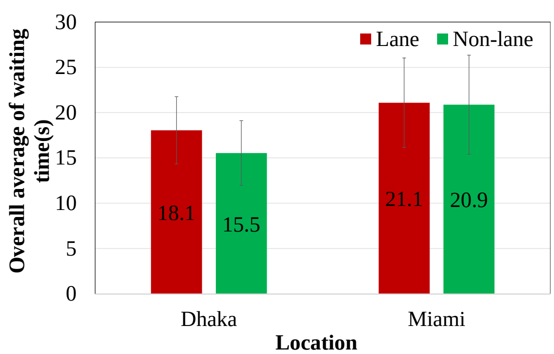


(f) Average speed of the vehicles in high generation rate with pedestrians

Fig. 6: Performance comparison based on the average vehicle flow rate of a link and average speed of the vehicles for Dhaka topology under various combinations



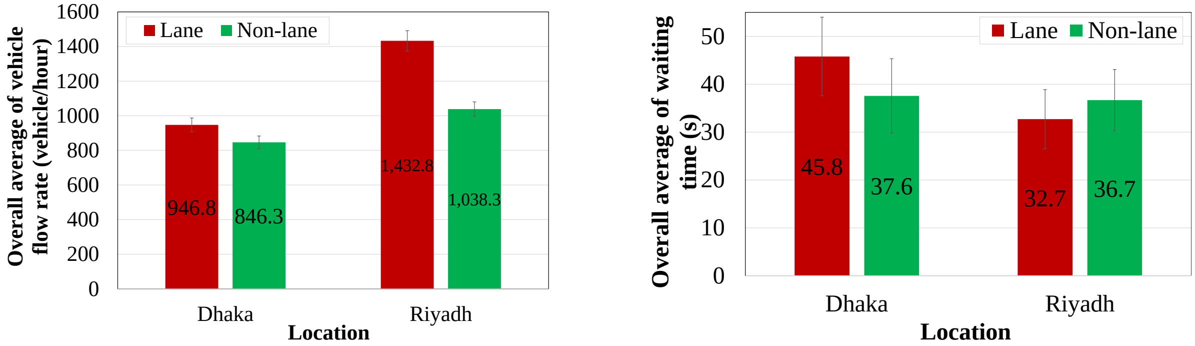
(a) Average vehicle flow rate with medium generation rate



(b) Average waiting time with medium generation rate

Fig. 7: Performance comparison between Dhaka and Miami traffic distribution in Miami topology

alter the performance of heterogeneous traffic stream but slightly decreases the performance of homogeneous ones. With heterogeneous traffic, non-lane-based traffic systems perform better when roads are narrow. Lane-based traffic outperforms non-lane-based traffic when traffic stream is homogeneous and roads are wide enough to accommodate lane-based systems.



(a) Average vehicle flow rate with medium generation rate

(b) Average waiting time with medium generation rate

Fig. 8: Performance comparison between Dhaka and Miami traffic distribution in Riyadh topology

From the above summary, we can say that only converting the traffic system of Dhaka into a lane-based system does not guarantee better performance due to the small, slow, human-powered vehicles, and narrow roads of Dhaka city. In addition, non-lane-based scenarios may provide better system performance in many cases such as emergency evacuations where one may expect a fair combination of slow and faster-moving vehicles. For example, lane reversal or contra-flow many times come into practice during major evacuations, however, such scenarios may benefit by adopting non-lane-based strategies. Moreover, RoadBird is capable of modeling behavioral phenomena such as pedestrians, bicycles, and signal control among others.

While we do not claim that establishing non-lane-based systems in all scenarios will eradicate the current problems overnight, we have clear empirical evidence that wide road networks can indeed benefit from lane-based systems. However, our experiments also show that narrower roads perform worse in lane-based systems. A natural future direction of our work would be to update our model with more complex and realistic parameters (e.g., traffic safety, road intersections, traffic signaling, pedestrians). Another plausible extension could be the usage of a combined setup of both lane and non-lane-based systems in the same topology. Moreover, such simulation techniques could potentially lead to new research directions of identifying more efficient strategies in major crises such as a hurricane or wildfire evacuation where demand typically exceeds capacity.

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